Growth of Lago Enriquillo

Final Report

Mentor: Jorge Gonzalez Ph.D.

July 2010

Lin Lin **Gary Bouton**
Karsha Walker **Alvin Molina**

Department of Environmental Engineering
Senior Design Project
The City College of New York
140th Street, New York NY 10031

Table of Contents

I. Abstract 3

II. Introduction 4

III. Background 7

IV. Problem Statement 8

V. Impact of the Problem 10

VI. Team Management Landscape 12

VII. Methodology 14

- a. Lin Lin 14
- i. Stream Flow 14
- ii. Surface Area - Change of the Lakes 14
- b. Karsha Walker 15
- i. Precipitation 15
- c. Alvin Molina 16
- i. Temperature 16
- d. Gary Bouton 17
- i. Remote Sensing of Land Use and Runoff Land Classification 17
- ii. Satellite Use and Remote Sensing Techniques 17
- iii. Integration 18

VIII. Results and Discussion 19

- a). *Lin Lin* 19
- i. Surface Area - Change of the Lakes 19
- ii. Average Lake Surface Area change and Growth Trends 21
- iii. Annual Variation 26
- iv. Hurricane Case Studies 27
- v: Volume estimation 29
- b) *Karsha Walker* 32
- i. Precipitation Analysis 32
- ii. Statistical Analysis of Precipitation and Lake Surface Area 39
- c) *Alvin Molina* 40
- i. Surface Temperature Analysis 40
- ii. Sea Surface Temperature Analysis 45
- iii. Statistical Analysis: Sea Surface Temperature – Surface Temperature 50
- iv. Extreme Events 51
- d) *Karsha Walker* 53
- i. Dew Point Temperature 54
- e) Summary of Lake Surface Area and Climotology Findings 54
- f) *Gary Bouton* 55
- i. Land Use and Runoff Land Classification 55
- ii. Hydrological Model Analysis and application 62
- iii. Recommendation and Forecasting 69
- g) References 73

I. Abstract

The Dominican Republic experienced several severe tropical cyclones during 2007, 2008 and early 2009 where increased precipitation caused rivers and lakes to be overloaded with excess rainwater. As a result, the rivers and lakes of the country have increased in size and flooded many areas surrounding them.

One of the watersheds that was severely affected is Lago Enriquillo; its size having increased considerably over years. Due to the increase in size of the lake, surrounding agricultural lands have been flooded resulting in loss of lands and livelihoods of the people. Although there were no obvious extreme events observed after the hurricanes of 2008 and storms during the first quarter of the 2009, the lake has continued to increase its size. Due to these unexpected conditions and the impacts of the flooding to the people in the local area, a team of senior students from The City College of New York is conducting a study to investigate the possible reasons for the expansion of the lake.

Lago Enriquillo is a closed lake that has no inflow or outflow—all of its water comes from precipitation (direct rainfall or surface runoff). Therefore, by investigating factors such as climate change (frequency of extreme events), land-use change, change of precipitation patterns, and the river network watershed we can determine and weigh how the changes in these factors has contributed to the expansion of the lake. Also by analyzing historical data of extreme events, precipitation, and changes in the surface area of the lake, we can identify if these conditions have happened in the past as a natural trend or if they are the result of new problems from improper land-use practice, climate change, or other environmental factors.

II. Introduction

The Caribbean region experiences a tropical climate all year round. The dry season spans December through May and the rainy season June through December, also referred as the hurricane season. During the hurricane season the region experiences mild to severe hurricanes/tropical cyclones. Hurricanes can induce changes in the landforms, change vegetation, influence human quality of life, and impact the economy of a region (Lugo, 2000). Hurricanes are accompanied by strong winds and increased heavy rainfall. The Dominican Republic is located around the center of the tropical cyclones paths in this region.

The Dominican Republic has a complex climate variation throughout the year and its topographic structure varies greatly throughout the country. The southern region of the island experiences drier weather conditions where average precipitation is approximately 600 mm annually. For example, in the Valle de Neiba, which is located close to Lago Enriquillo, the average precipitation is as low as 350 mm annually. While in the northern region of the island, average precipitation is approximately 1,800 mm. The Cordillera Oriental, located in the eastern part of the island, experiences as much as 2,740 mm of rainfall annually. The country has two distinctive weather seasons, a dry season and a bimodal rainfall season. The dry season extends from December through March. There are two classifications of the rainfall season, early and late. The early rainfall season extends from May through June with a brief dry period in July and the late rainfall season extend from August through November with peak rainfall in October.

The Dominican Republic contains four major mountain ranges: the Cordillera Septentrional on the north; the Cordillera Central at the center where the highest mountain in the West Indies with peak of 3,098 meters above sea level is located, Sierra de Neiba at the south of the Cordillera Central, and Sierra de Bahoruco on the south. Lago Enriquillo is at the valley of the Cordillera Central and Sierra de Neiba mountain ranges and it is about 40 meter below sea level.

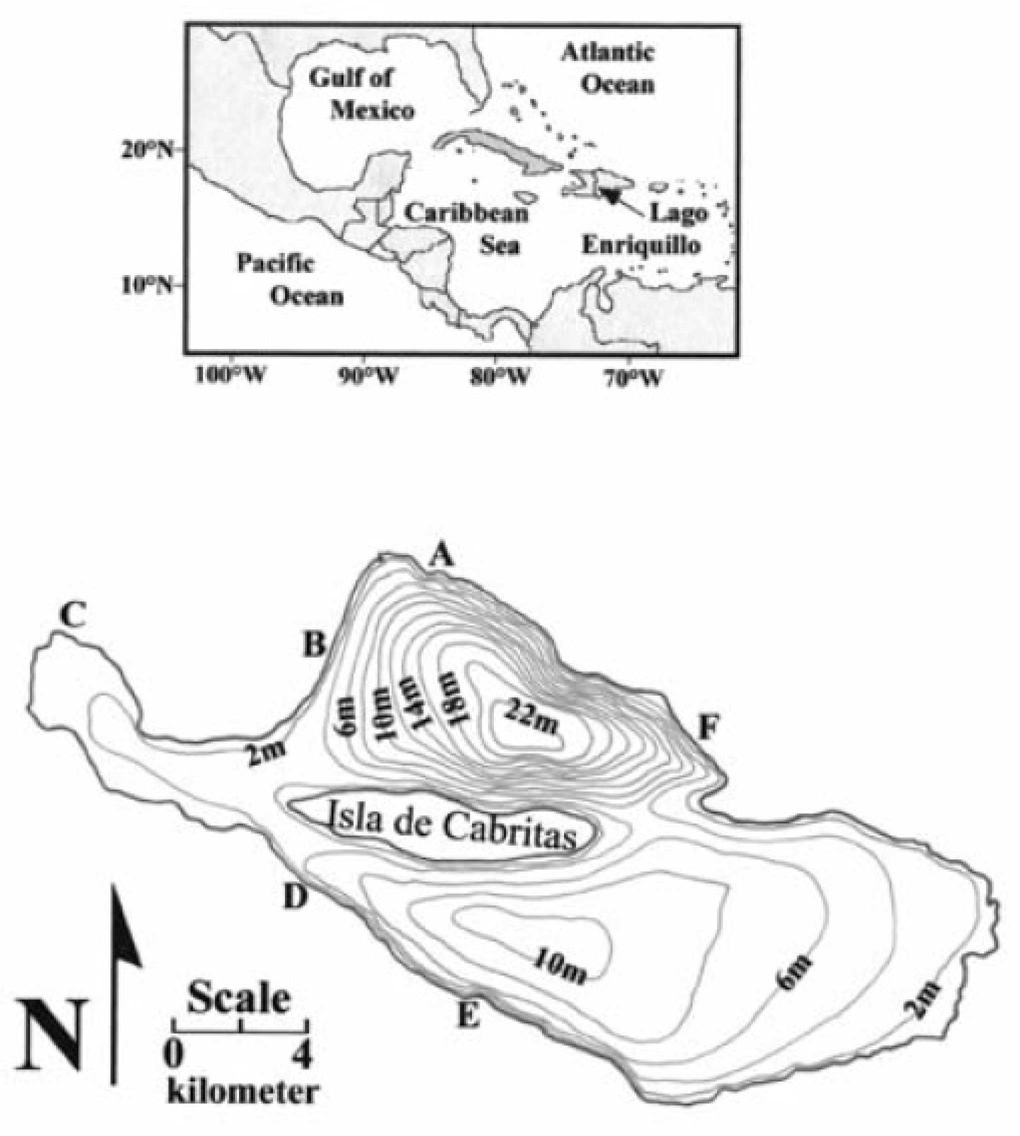


Figure 1 - *Lake Location, Bathymetry*
(Source: Image from Buck, 2005)

Figure 2 - *Topography of Dominican Republic. Topographic map of Dominican Republic, Lago Enriquillo (Hoya Lago Enriquillo) is identified by the red arrow on the left of the image.* (Source: http://www.rimd.org/advf/documentos/4b63411256f9b.pdf)

From late 2009 to present, there has not been any severe tropical system impacting the island with increased precipitation. However, the lake continues to grow in size in the absence of severe perceptive events (*Medrano, P. 2009*). Due to the complex climate and topographic system that the Dominican Republic has, it is hard to identify the causes for the continued expansion of the lake. In order to understand the possible factors that contribute to the problem, we have decided to approach the problem from different factors: land-use, extreme precipitation events, climate changes, river network, and temperature to combine our result to analyze how have these factors impact the size of the lake.

III. Background

Lago Enriquillo is located in southwestern region of the Dominican Republic (18°31.7’ N, 71°42.91’ W) between the towns of Independencia and Bahoruco. It is the biggest lake in the country and in the Caribbean with an area of 265 km^2. The lake contains three small islands that lie below sea level: la Isla Cabritos, la Isla Barbarita, and la Islita. The fauna of the lake consists of reptiles and birds. The flora consists of cactus and dry forest.

Lago Enriquillo is a hypersaline lake of marine origin separated from the Caribbean ocean by tectonic uplift and fluvial damming by the Yaque del Sur River. The lake lies 40 m below sea level and has twice the saline content of the nearby sea that fluctuates from 30 ppt to 100 ppt due to seasonal rainfall/dry seasons. The major rainy season correlates with the region’s hottest months, mid-May to late-October. The southern watershed is a semi-arid tropical zone with scant natural vegetation and an average rainfall of 600-700 mm per year while the northern watershed, fed mostly by the Yaque del Sur River, averages 1,800 mm annually and is a major source of fresh water for irrigation. Lago Enriquillo has one outlet, which is evapotranspiration, ranging from 1,200 mm to 1,800 mm and during prolonged dry spells can outpace the inflow of fresh water upwards of 2,500 mm. Severe seasonal evapotranspiration was the prevalent mechanism affecting Lago Enriquillo’s size and salinity before the 1990’s. Canals from the Yaque del Sur River were made to sustain levels and salinity to protect the natural salt marshes of the lake which are home to several endemic species of lizards, alligators, and migratory birds.

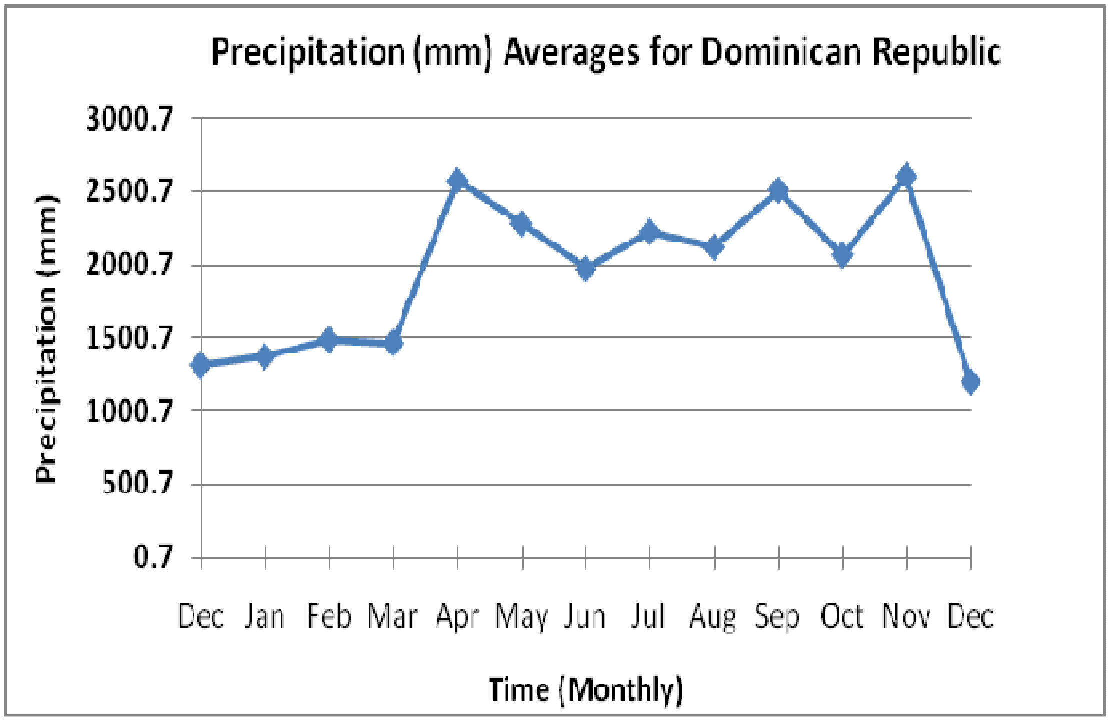


Figure 3 - *Average Precipitation (mm) for Dominican Republic*
(Source: Modified Eco-Casting model: The Dominican Republic, CCNY)

IV. Problem Statement

Lago Enriquillo is a closed, land locked lake hydrological system with no contributing river/stream sources and no discharge outlets. Its only source of water is from precipitation, either from the direct rainfall on to the lake surface, runoff from the nearby land surface, or from the flooding of the nearby river/stream during the precipative periods. The purpose of this project is to research and discover through remote sensing techniques the causes for the expansion of Lago Enriquillo by looking at the following environmental local factors:

- direct rainfall on the lake surface
- estimation of amount of runoff during flood episodes from land surface and river/stream
- land use changes
- climate changes
- lake expansion rates

Currently, there are questions regarding the longer episodes of flooding in the Lago Enriquillo River basin and its current salinity issues. Flooding issues may be consequential to the recent lengthening of the rainy season's duration and increased intensity as well as the frequency of tropical storms/hurricanes hitting the Dominican Republic in recent years (2002 – present). This can be verified by using techniques in remote sensing in correlation with historical data to study current lake growth and understanding land use of the surrounding areas. Using the collected information and modeling techniques of the local hydrology mechanics, our group can suggest mechanisms to abate future flooding in flood prone areas by producing models that can explain trends.

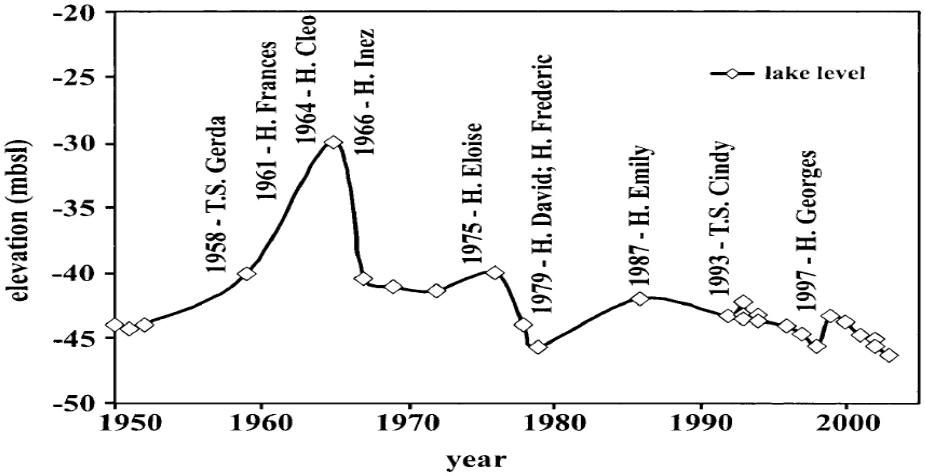


Fig. 4. Elevation of Lago Enriquillo in meters below sea level (mbsl) from 1950 to 1963, and the timing of hurricanes (H.) and tropical storms (T.S.) passing near the Enriquillo basin. Lake level data were provided by Roberto Cruz, Tesis Duquela-Gonzalez, and Juan Saldaña of Indrhi (pers. comm..). Hurricane and tropical storm data are from the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center (http://www.nhc.noaa.gov/). Irrigation canals constructed around Lago Enriquillo in the 1960s may account for the muted response of lake level to storm activity since the 1970s.

Figure 4 - *Past Tropical Storms Events and Lake Level* (Source: Image from Buck, 2005)

Figure 4 details the effects of Hurricanes and Lago Enriquillo's water level and how improved canal and water management irrigation stabilized the level. It is believed that accelerated agriculture has put a strain on the exiting irrigation network causing some old dykes to break due to poor construction or increased silting due to runoff (Buck, 2005).

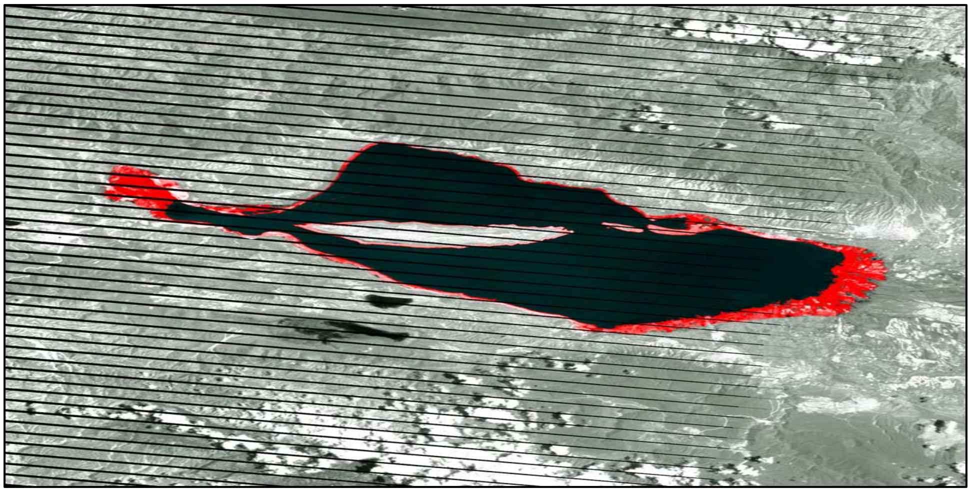


Figure 5 - *Red area is the flooded area of the lake after hurricane of 2008* *(Image produced by NASA after Hurricane of 2008 by NASA/Landsat, Mike Taylor)*

A flooding event in early 2009 impacted 16 communities; 10,000 families; and more than 18,865 hectares of agricultural/pastures land around the lake (*Medrano, P., 2009*). Therefore, it is essential to study the factors that might contribute to the expansion and ask questions such as how the land-use impacts the amount of runoff from rainfall the lake receives, how the variation of rainfall contributes to the size of lake, and how much water is contributed by the flooding of the nearby rivers/streams during the heavy rainfall. This will help us simulate different scenarios for the lake, predict how much it could expand, and suggest possible mitigation methods.

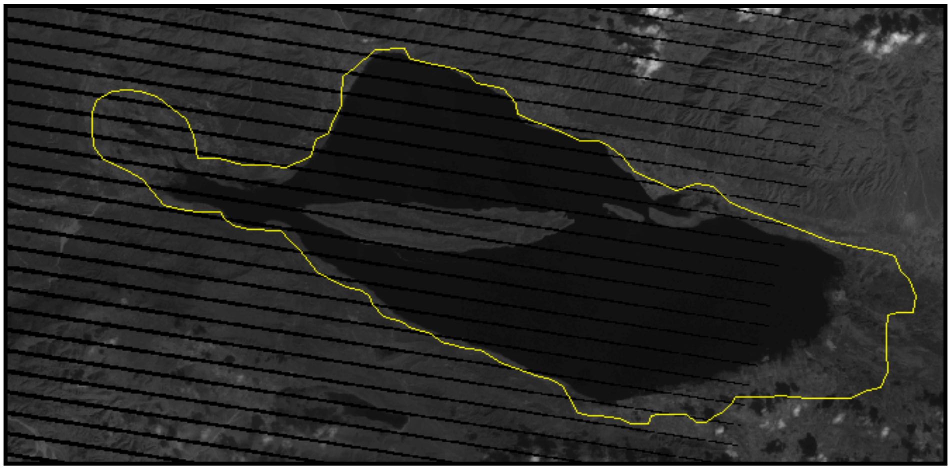


Figure 6 - *Change of Lake Surface Area from 2006 to 2009***.** *Lake surface area expanded to the yellow border during the extreme events happened in past three years*

V. Impact of the Problem

Lago Enriquillo is one of the largest inland water surfaces in the Dominican Republic. The encroaching water of Lago Enriquillo has destroyed farmland and pastures by flooding the soil with its hyper-saline waters. Losing farmable acreage creates stress on the existing crop yields causing the Enriquillo basin populace to run into shortages of irrigation dependent crops such as rice, which are local foodstuffs. As a result, outside agencies need to be brought in to assist with moving families out of the flood plain, supply food and drinkable water at a high cost. [*IFAD, 1998]*

In early 2009, an episode of flooding occurred in the Lago Enriquillo region due to heavy rains occurring outside its normal rainy season causing many productive farmlands to be abandoned and the local farming community's assets to be lost. This situation required the assistance of the World Food Programme to step in and distribute aide and funds to those affected.

Latest data made available by the Secretaria de Agricultura indicates:

- flooding of 16 communities in two provinces
- 10,000 affected families
- over 18,865 hectares of agricultural and/or pasture land flooded
- flooding and damages to some 1,000 properties

(Source: Medrano, P. 2009)

Environmentally, the challenge is to keep Lago Enriquillo clean of runoff from top soil due to inferior slash and burn techniques that the local farmers participate in to clear more farmable fields. This causes less rain water to be held in the soil and causes mudslides and silting into the lake itself, creating a situation in which fertilizers, solid wastes, and minerals are entering the waters of the protected parkland. Runoff also contributes to flooding by increasing the lake's size and pushing its borders closer to towns/villages in the immediate area. A threat arises because it brings the American Crocodile, which calls Lago Enriquillo home, closer to the general populace and increases the chance of attack *(Dominican Today).*

This also puts a burden on the growing Eco–Tourism sector that has been seeing alarming growth. More frequent flooding cuts off access to the lake area itself and many tourism operations suffer great loses locally to their equipment and offices. The destruction to the habitats of endemic species in the Lago Enriquillo region is also of concern during flooding as waste water and local area pollution collects in the lake killing animals and raising toxicity levels *(Hernández, 2003).*

Health concerns also arise during flooding. Currently in the area 72% of the population has easy access to water, with 78% having access to drinking water. However, only 47% are serviced by regular garbage collection—a figure considered extremely low and a high-risk factor for human health [Ref]. These percentages are severely strained during flooding episodes when access to clean water is compromised and garbage ends up with the runoff into the lake. Cases of disease (i.e. dengue, malaria, diphtheria) rise with flooding and access to local hospitals in the province of Independencia are hampered forcing patients to be taken to hospitals further away. There were no cases of meningococcal meningitis or leptospirosis in the 2004 floods, but increased flooding mixed with runoff of solid wastes increases the risk of transmission of these diseases to the local communities *(The Pan American Health Organization).*

Recent research suggests that flooding of Lago Enriquillo will continue to worsen as the precipitation seasons and their severity worsen with higher sea surface temperatures (SST) and sea level risings due to global warming. With increased agricultural pressure on land use in the area, predicted increases in poor irrigation techniques, and slash and burn farming we can expect more runoff and silting into the Lago Enriquillo basin from its canals and dyke system. Improperly built canals and dykes can strain the natural watershed system and cause floods further up river. The market for a solution is that properly planned agriculture expansion is dependent on the canal system and the proper construction and safety of its network for a net return of profit and growth for the growing local population and the burgeoning local agro driven economy (*Environmental Priorities and Strategic Options Country Environmental Analysis).* This makes understanding Lago Enriquillo's current behavior and contributing factors to the problem important so that a solution may be suggested on how to move forward.

VI. Team Management Landscape

Team has decided to approach the project with different methods, and each team member is working on a specific way to approach the problem as described in their methodology section. One timeline chart is produced to show the whole project timeline and for each member to follow through the timeline to complete the task on time. If any member has difficulties or obstacles while working on their task, they should immediately notify other members and have a meeting setup as soon as possible to resolve the issue and continue forward.

Table 1: Project Timeline from Week February 22, 2010 to March 22, 2010

Member/week	Feb 22	Mar 1	Mar 8	Mar 15	Mar 22
Lin	- Contact with Dr. Balazs for Hydrosheds data -Search for streamflow information about the lake	-Obtain basic GIS shapefile/raster file of the study area -Working on proposal	-Finish combining all parts of proposal -Download basic river network data and DEM of the study area, and start download Landsat data	-Download and order all Landsat data from 1980 to present -Check for availability of quantitative stream/river data	- Start writing code for finding the surface area of the lakes
Gary	- Work in obtaining percip records	- Acquire Landsat, ASTER, MODIS imagery	- Write program to identify hist. flooding events and rates	- Used sat images to find baseline in hist. land use	- Map changes in land use
Alvin	- Get in contact with the Meteorology National Institute - Research and collect data of the sea temperature in the Caribbean	- Compile and plot graphs on excel to look for changes and interpret results	- Analyze the collected data - Research about the different factors that are responsible for the formation of storms in the Caribbean	- Compile the collected data of the sea and ground temperature - Plot the temperature changes ground vs. sea into graphs and analyze results	- Research for the different factors that have increased or lowered the temperature in the Caribbean area and how much it has changed in the Dominican Republic compare to the other countries
Karsha	Research historic climate information and data for the region including precipitation	Research extreme events information and data. Research bathymetry data for Lago Enriquillo	Begin basic statistical analysis of available data for precipitation. Work on proposal	Research bathymetry data for Lago Enriquillo. Research for more precipitation data	Download remainding precipitation data from NCDC

Table 2: Project Timeline from Week March 29, 2010 to May 3, 2010

Member/week	Mar 29	Apr 5	Apr 12	Apr 19	Apr 26	May 3
Lin	-Continue working on writing code for surface area - Find the discharge of the river/stream in the watershed,	- Finished measuring surface area of lakes from the available data - Estimate amount of overflow from them during flooding	- Compare the surface area changes of the years	- Work with team to put all results together, and discussion about the result we got	- Look for a modeling or simulation program to estimate the expansion of the lake with different scenario (neural modeling)	- Prepare final report - Prepare presentation for final result
Gary	- Develop run off coefficients for land use types	- Factor in rainfall vs. runoff scenarios to determine contrib. to lake size	- Develop future land use prediction	- Develop future rainfall prediction	-Use MATLAB to model level of lake changes with former two models Neural Network Training	- Final report and presentation
Alvin	- Finish the compilation of information of the different variables that are studied	- Analyze results with team member in order to recreate the different scenarios	- Create the different scenarios to analyze the changes that could affect the region	- Travel to the Dominican Republic to study and see the actual situation of the region	- Analyze the data that was collected in the trip and comparing with the different scenarios that we created	- Put all the information together. - Prepare final report and PowerPoint presentation
Karsha	Begin Extreme events statistical analysis.	Complete both precipitation and extreme event statistical analysis	Work with Gary to do Matlab coding for images and plot graph and charts using Microsoft excel for precipitation	create images and graphs for extreme events using Arc GIS or MatLab	Do final analysis of final products to determine any relation between precititaion and extreme evnts	Comoile final product by integrating all analyses. Prepare Final report and presentation.

VII. Methodology

a. Lin Lin

i. Stream Flow

The Dominican Republic has a complex river/stream system due to the precipitation variation of the season; some stream/river appears and disappears upon the amount of rainfall. Lago Enriquillo is a closed lake that has no connected outflow or inflow. All of its water comes from rainfall, which includes the direct rainfall on the surface of the lake, runoff from surface of the watershed, and flooded water from the river/stream during heavy rainfall. Therefore, it is essential to identify how many river/stream in the watershed there are, what the discharge rate is, and how much they contribute to the lake during heavy rainfall periods. Using data downloaded from USGS Hydrosheds (**Hydro**logical data and maps based on **SH**uttle **E**levation **D**erivatives at multiple **S**cales) as a base to understand the stream flow condition around the lake, we can then get the quantitative discharge, dimension of the stream/river data from the Dominican Republic if possible, and estimate the amount of overflow from the stream/river with certain amount of rainfall.

- Download flow direction / flow accumulation / river system / water basin / Digital Elevation Model from HydroShed database and load them into ArcGIS
- Request stream/river information from the Dominican Republic for quantitative data of the river/stream
- Identify which of them can possibly contribute during the heavy rainfall (by using the elevation data, find the river/stream locate at a place that would have the gradient toward the lake)

ii. Surface Area - Change of the Lakes

Using satellite images of Lago Enriquillo and Lake Azuei from Earth Explorer database (all possible non-cloudy images from landsat1 to landsat7) along with ArcGis or MATLAB, the surface area of the lake can be measured. By downloading data from 1980 to 2010 and measuring its surface area, we can see the pattern of the flooding or drying of the lake. This method is considerable because the bed rock of the lake is assumed to have no changes over the 30 year period. Therefore, if the level of the lake increased then the surface area should have increased also since the boundary of the lake is not vertical. By using this method, we can have a big picture understanding of the growth patterns of the lake by observing any year interested. We can see the long term trend of the lakes, and if there is any correlation between the two lakes since there is concern for the possibility of a connection between two lakes.

The following tasks will be conducted to complete this activity:

- Order and download the available images from Earth Explorer
- Select the measurable images.
- Use the Area measurement tool to find the surface area of the lake three times and take the average to minimize the error of measurement. (or use programming to find surface area of the lakes)
- Plot the area verse time of the 30 years data, look for pattern of lake, and correlation between the lakes.

b. Karsha Walker

i. Precipitation

Over the past years the Dominican Republic has experienced increased rainfall associated with climate change events and change in weather patterns in the region of the Caribbean. In this section, the focus is on precipitation and extreme events in region of Lago Enriquillo. For the purpose of this project, extreme events are classified as hurricanes and floods.

Two very important problems that arise from climate change events for the Dominican Republic are temperature changes and precipitation changes. As the levels of green house gases increase, global temperature are predicted to increase along with increases in atmospheric water vapor concentration which affects global energy balance and leads to more intense rainfall events. Trends are also beginning to indicate that hurricanes and typhoons are becoming more intense—the central pressure is dropping, the peak wind speeds are increasing, and, to power these changes, more energy is being derived from the condensation of the water vapor that is present as a result of the warmer sea surface temperatures, and resulting in more intense rainfall. In addition, global climate change will affect the large-scale circulations of the atmosphere and oceans (the strength and phasing of the intertropical convergence zone) and the characteristics of hurricanes [*MacCracken*]. Based on this information, it is appropriate to do a precipitation and extreme event analysis to determine how these factors correlate with the expansion the Lago Enriquillo and its periods of flood events.

Lago Enriquillo has no connecting inlets or outlets. By analyzing precipitation data, precipitation patterns and extreme events data from the last 30 years, 1980 – 2010, we will try determine any relation between with these parameters and the increase of the lake. Using hourly data downloaded from the National Climatic Data Center (NCDC) for the Barahona station located at 18’13”N and 071’06 W in the Dominican Republic, a complete statistical analysis will provide useful and important information such as the average precipitation, minimum and maximum rainfall levels, and rainfall peak intensity. The data will be analyzed in periods of years, months and weeks. This analysis will determine periods of extreme precipitation in the region. Using MatLab and/or Arc GIS, images and graphs will be created to provide visual analysis. Using flood data and hurricane data from the NCDC and NOAA, a complete statistical analysis will also be done. Images and graphs will be created and coupled with precipitation data to determine possible correlation.

c. Alvin Molina

i. Temperature

A study of temperature changes in the area close to the lake over the last 30 years is another key factor in finding causes behind the increase of the lake. The first step is to get in contact with the Instituto Nacional de Meteorologia (Meteorology National Institute) of the Dominican Republic in order to request data that reflects the changes in the period of time mentioned. By compiling the information and plotting it in Excel, a study of the difference in temperature over the last three decades can be analyzed. This will allow measuring the amount of evaporation in the region and the formation of water by the condensation of vapor water in the atmosphere that will essentially pour more water in the region. By estimating the amount of water that could be poured by this condensation and the deforestation in the area, an estimation of how much water can be added to the lake or the amount of water that can be lost from the lake due to evaporation can be measured.

The changes in the sea temperature around the island during the last 30 years will also be studied. The procedure will be similar to the one explained previously with the only difference being the factors that could be altered by the increase in the sea temperature and how much the island could be affected will be studied. An increase in the sea temperature will lead to higher humidity in the area that could produce strong and frequent storms that would pour a significant amount of water, especially during the hurricane season that runs from June through November when the temperature of the sea is at its highest. By looking at how much the sea temperature has changed and how many storms could be produced in the region, scenarios of possible flooding situations can be created by using remote sensing and ArcMap. This will allow estimation of how much water could come from those storms and could go to the lake and estimate the increase in size of the lake due to those storms.

Looking at other scenarios within the Caribbean region that also correlate with sea surface temperature and precipitation rates, we can identify similarities and differences with what is happening locally at Lago Enriquillo to the regional trends. This can be used as a tool to decipher whether Lago Enriquillo acts as an isolated incident due to other factors such as wind, temperature, topography, and topology. The next step is to get in contact with the different meteorology agencies at the different countries to request data of the temperature for the last 10 years.

d. Gary Bouton

i. Remote Sensing of Land Use and Runoff Land Classification

A technique to identify water sources for the causes in lake level rise in Lago Enriquillo would be to analyze the historical land use satellite images coupled with precipitation trends. Runoff is defined as the amount of precipitation that would normally be absorbed into the ground water systems but instead the soil absorption capacity is exceeded causing the water to flood elsewhere down the watershed region. Runoff rates can alter based on how the land use changes with regards to runoff coefficients being assigned to land types based on their soil moisture uptake rates and their effect on ground water infiltration. Land use changes and increased runoff is a huge problem in modern society as primary and secondary forests are cleared for ever increasing farmland, roads, and cities.

This is important data to consider because in the Lago Enriquillo region agriculture and pasture use has increased in the region due to the proximity to underground fresh water springs in the region and major rivers like the Yaque del Sur River. Many smaller villages have also sprouted up in the region and a portion of the farming in the area is primarily subsistence farming. Most of the local farmers employ improper clearing techniques, such as slash and burn farming, as methods to clear fertile fields and land use changes become an important equation in whether this is causing an increase in run off percentages into the lake itself.

This data could also be useful in predicting the causes and cases of flooding in the Enriquillo basin where the effects hamper villages and cause destruction and health concerns. The data can be used to identify where land use changes are causing the most stresses on the natural watershed thereby identifying where more methods of proper damming, irrigation or replanting of forest could be more useful and less costly then the damages caused by the increased flooding in the region. Then future models could be developed which account for trends in the land use change coupled with scenarios of precipitation to show how changes in climate, precipitation, and land use scenarios will affect the region.

ii. Satellite Use and Remote Sensing Techniques

Land use can be determined with the aid of LANDSAT images with its long running data imagery acquisition records which help create a historical baseline in which we can develop a historical overlay of mapped land use changes against. By using this data coupled with historical data of land use in the region we can measure the growth of farmland and the movement of primary and secondary plant life which has a greater tendency to hold soil moisture and lessen runoff, unlike techniques of clearing land by slash and burn farming *(Dominican Republic - Environmental Priorities and Strategic Options Country Environmental Analysis).*

Band math can then be used to measure the coefficient rates of runoff of the land which has an accurate detection for soil type changes in bare agricultural soils. This technique works well for tracking run off changes due to land parceling or improvements due to agriculture. *(Al-Khaier, F., 2003*).

iii. Integration

Using our collected rainfall data and qualifying rainfall that contributes to what a flooding event is considered in that region, we can then import this data in conjunction to our runoff coefficients to show which regions of land use contribute the most to runoff scenarios during flooding. We can then apply weighted percentages on rainfall scenarios if runoff itself is the major contributor to lake level rise.

Neural Network applications, a toolbox function done through Matlab processing software which can be trained to identify flood/no flood scenarios in parallel with known Watershed mapping, can use our collected rainfall data, land use data, and known evaporations rates to provide future planning or monitoring of changing events in the region for the future.

VIII. Results and Discussion

a. Lin Lin

i. Surface Area - Change of the Lakes

Since the study is about the expansion of Lago Enriquillo, it is important to visualize and quantify the surface area change of the lake over the past 30 years, the change before and after a rainfall or hurricane event, and correlate the change in surface area to the amount of precipitation during the event. Measuring the surface area of the lake over the past 30 years can identify if there is a pattern of growing and shrinking, how the lake has changed over time, and link similar cases of hurricane effects on the size of the lake. This method is valid because there have been no major changes to the depth of the lake over the past 30 years. Therefore, if the level of the lake increases then the surface area should have increased since the boundary of the lake is not vertical.

The satellite images used for this study are Landsat1 to Landsat7 taken from the U.S. Geological Survey Earth Explorer database (http://edcsns17.cr.usgs.gov/EarthExplorer/). All available non-cloudy images were downloaded from the database from 1984 to 2009. The surface area of every image is then measured ArcGIS manually. The following tasks are completed for this method of study:

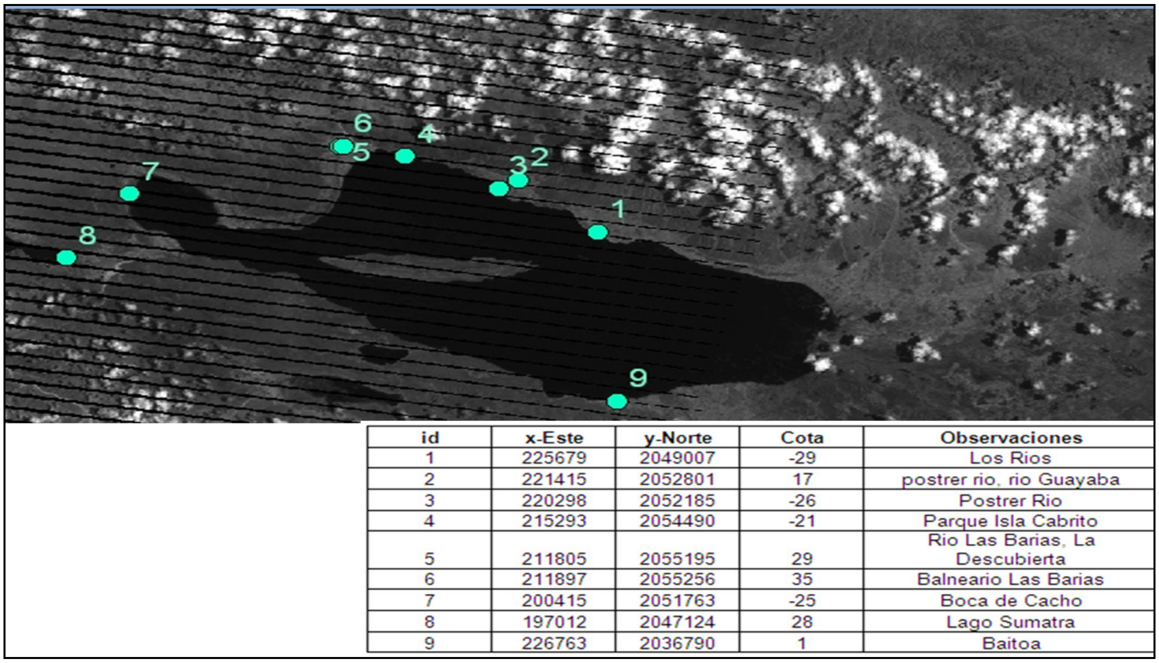
- Order and download the available images from U.S. Geological Survey's Earth Explorer Database
- Select the measurable images
- Use the Area measurement tool to find the surface area of the lake three times and take the average to minimize the error of measurement (Since the measurements are done manually, there is an expected percentage error of 5% to 10%)
- Plot the area verses time for the 30 years of data to identify a pattern of the lake
- Pick case studies and compare the lake surface area before and after a specific hurricane event
- Use the surface area measurements for other analysis (including correlation with other method of analysis, incorporate with DEM to find volume, and find affected area if lake level is ± 10 meters

Table 3 contains the number of images used each year for the surface area study from 1984 to 2009. Some year has less data due to cloudiness and some years are missing such as 1993 to 1995 (can't find any Landsat from 1993 to 1995 in online databases from USGS).

Table 3: Number of Landsat images used per year

Year	# of images	Year	# of images
1984	3	1999	9
1985	5	2000	14
1986	16	2001	12
1987	4	2002	9
1988	5	2003	6
1989	6	2004	13
1990	4	2005	13
1992	4	2006	12
1996	5	2007	15
1997	5	2008	13
1998	8	2009	19

The method of using Landsat to measure surface area is validity through the onsite measurement to Lago Enriquillo and Lake Sumatre on June 15, 2010. We visited nine locations around the lakes; at each location we measured their coordinates and elevation using a GPS. Then plot these data points into ArcGIS. These locations match the latest Landsat image (May 2010), and the elevation is in ± 5 meters from the DEM of the area. Figure 7 is a map showing the locations where the measurements are taken.



id	x-Este	y-Norte	Cota	Observaciones
1	225679	2049007	-29	Los Rios
2	221415	2052801	17	postrer rio, rio Guayaba
3	220298	2052185	-26	Postrer Rio
4	215293	2054490	-21	Parque Isla Cabrito
5	211805	2055195	29	Rio Las Barias, La Descubierta
6	211897	2055256	35	Balneario Las Barias
7	200415	2051763	-25	Boca de Cacho
8	197012	2047124	28	Lago Sumatra
9	226763	2036790	1	Baitoa

Figure 7: Onsite measurement locations in blue points. (Please note that the points are exaggerated to show the visited locations)

ii. Average Lake Surface Area change and Growth Trends

Figure 8 below is the average surface area of the Lago Enriquillo from 1984 to 2009. The figure shows in 1984 the lake's surface area is approximately 276 km^2 and gradually decreased until 1996, when the surface area shrinks to 172 km^2. After 5 years of growing from 1996 to 2001, the surface area of the lake decreases again until 2004, when it reaches the lowest point of this dataset with an area of 165 km^2. Beginning in 2004, the lake grows gradually and hurricane Noel in 2007 starts the exponential growing of the lake.

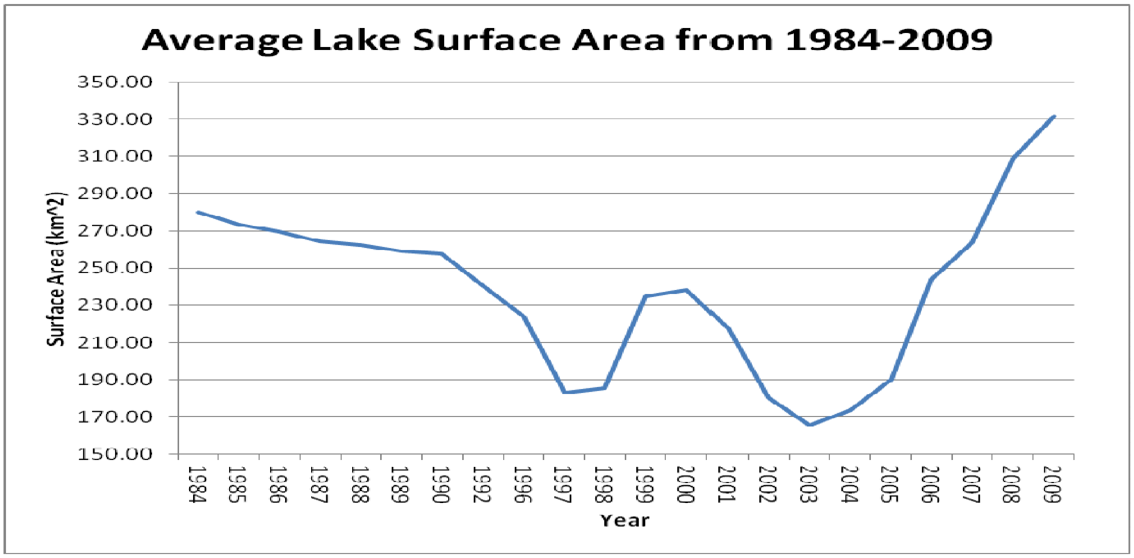


Figure 8: Lake surface area from 1984 to 2009

In 2006, the lake reaches the same size it was in 1984. Because the lake is already decreasing in size at the beginning of the dataset used, the original size of the lake could be bigger than its size in 1984 and it may still be growing back to its original size. At the end of 2009, based on the surface area measurement on December 29, 2009, the lake surface is 333 km^2. This is 17% larger than its size in 1984 and 49% larger than its size at 2004. Figure 10 shows the average surface area border for 3 years—1984, 2004, and 2009. Table 2 shows the average surface area of the lake from 1984 to 2009.

Figure 9 shows the growth of Lake Sumatre on the Haiti side of the island; this is a fresh water lake that is currently about 2 km away from the Lago Enriquillo around the Haiti and Dominican Republic border. Lake Sumatre has a similar growth pattern from Lago Enriquillo, especially in the past decade, where there is a decreased in 2003-2004, then started to increase again at 2005, and grow much faster after 2007 to its current size of 134.26 km^2.

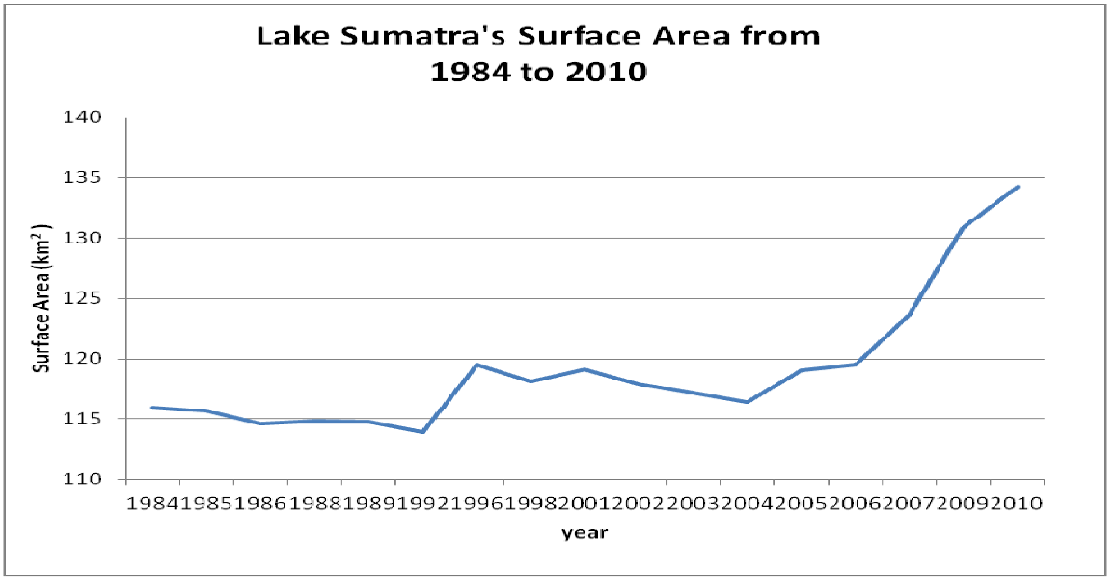


Figure 9: Surface Area of Lake Sumatra from 1984 to 2010 based on Landsat (using the latest image available on Earth Explorer Server of each year up to May 2010).

Lake Sumatra has an overall increasing trend, it didn't go through a sharp decreasing period like Lago Enriquillo, and it continues to grow from 1984 in general. Its size is 115.96 km^2 at 1984, and 134.26 km^2 at May 2010, about 15.8% increased in 26 years.

Table 4: Summary of Lago Enriquillo surface area from 1984 to 2009

Year	Area (km^2)	% Area changes	Year	Area (km^2)	% Area changes
1984	279.96		1999	234.86	26.60%
1985	273.50	-2.31%	2000	238.05	1.36%
1986	269.65	-1.41%	2001	217.34	-8.70%
1987	264.34	-1.97%	2002	180.06	-17.15%
1988	262.61	-0.66%	2003	165.38	-8.15%
1989	258.97	-1.39%	2004	173.68	5.02%
1990	257.85	-0.43%	2005	190.24	9.54%
1992	240.66	-6.67%	2006	243.79	28.15%
1996	223.86	-6.98%	2007	263.86	8.23%
1997	183.15	-18.18%	2008	308.88	17.06%
1998	185.52	1.29%	2009	331.78	7.41%

According to Table 4, the percentage change of the area is relative to the surface area of the previous year. The extreme percentage changes in 1997, 1999, 20002, and 2006 are the years when the area between biggest island, la Isla Cabritos, on the lake and the coast (this area is circled in yellow in figure 10) is connected and disconnected again due to the surface area changes.

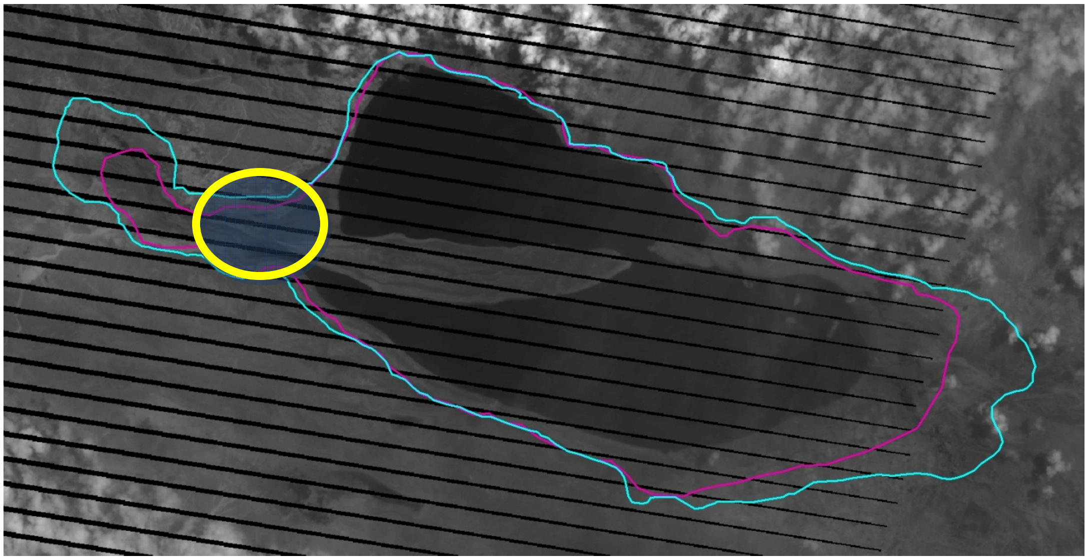


Figure 10: Lake surface area borderlines at 1984, 2004, and 2009

The base image of Figure 10 is the lake size in 2004, a year that the lake begins to grow again. The red line is the lake border in 1984 and the blue line is the border at the end of 2009. The expansion of the lake is mostly to the southeastern side and a little on the western tip, according to Figure 10. The area between the island la Isla Cabritos and the coast on the western side is connected in 2004. The other two smaller islands, la Isla Barbarita and la Islita, are completely submerged in 2009. The growth direction is also supported by Figure 11, which is a plot showing the border of the lake from 2000 to 2009. Figure 11a shows the shrinkages of the lake from 2000 to 2004 and figure 11b shows the growth from 2005 to 2009. Both the growth and shrinkage are intense at the western and southeastern portion of the lake.

The percentage change of the surface area in the four directions is calculated by using the ratio of area change in each direction over the total area change that year. The division of each direction is marked with red lines in Figure 11. Area change on the left of the red line is considered the west. Area change on the right of the red line is considered the east. Area change in between both lines is north and south for northern and southern portion respectively. Table 5 contains the measured percentage changed.

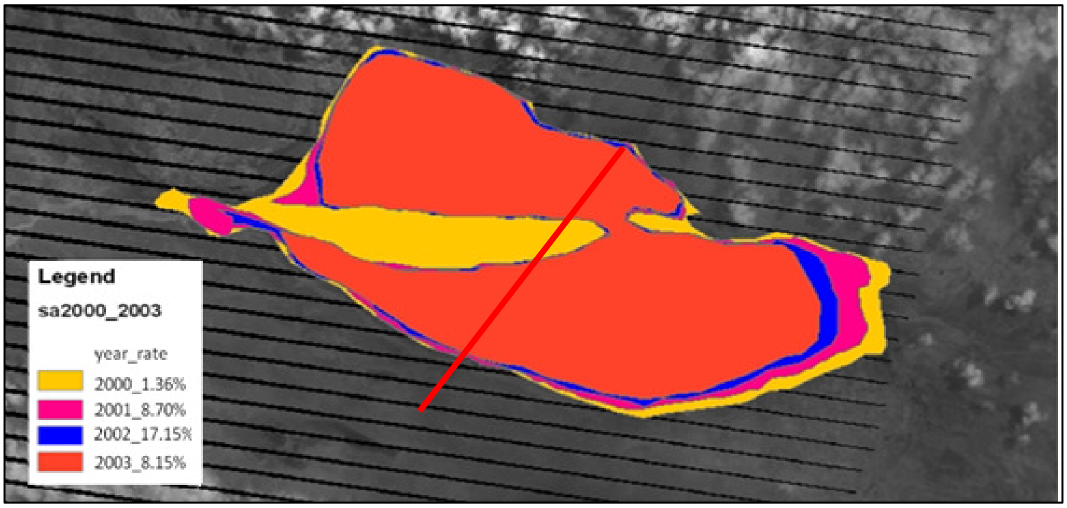
Table 5: Percentage change of the lake in direction

Year	Area (km^2)	Area change (km^2)	% change on north	% change on west	% change on south	% change on east
2004 to 2005	173.68	16.56	11.47%	39.25%	15.10%	73.07%
2005 to 2006	190.24	25.55	10.53%	15.66%	10.96%	55.58%
2006 to 2007	243.79	20.07	6.48%	32.39%	18.93%	74.24%
2007 to 2008	263.86	45.01	8.44%	21.33%	8.22%	59.98%
		average change	9.23%	27.16%	13.30%	65.72%

(Note: The area change from 2005 to 2006 is discounted for the area of island la Isla Cabritos, which is 28 km^2.)

Table 5 supports the prediction of lake expansion mostly toward the southeastern and western portion of the lake. The percentage change on the west side ranges from 15% to 39% and 55% to 73% on the east side, and around 10% on each of the north and south sides. The total percentage does not add up to 100% due to measurement errors.

11a)



11b)

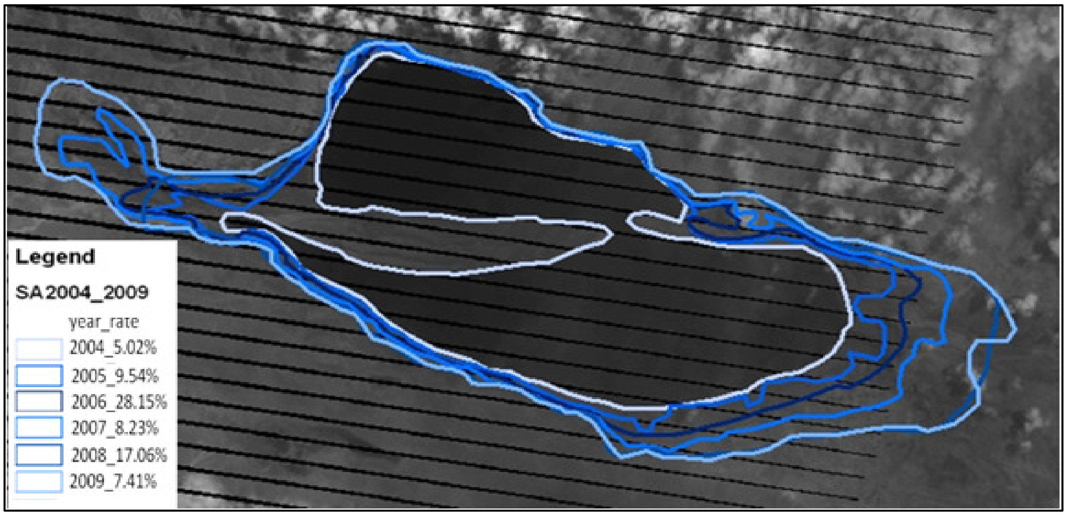


Figure 11: Figure (11a) on top is the shrinking period of the lake from 2000 to 2004. Figure (11b) on the bottom is the growing period from 2005 to 2009. The red lines on Figure (11b) is used to divide the directional changed calculation above.

Lago Enriquillo has found to increase about 10 meters on both East and West coasts. This is done by using Landsat images at different date; locate 10 points or more at the coast, and use DEM file to find the elevation of the points. Then average the points to get the elevation of the lake each year.

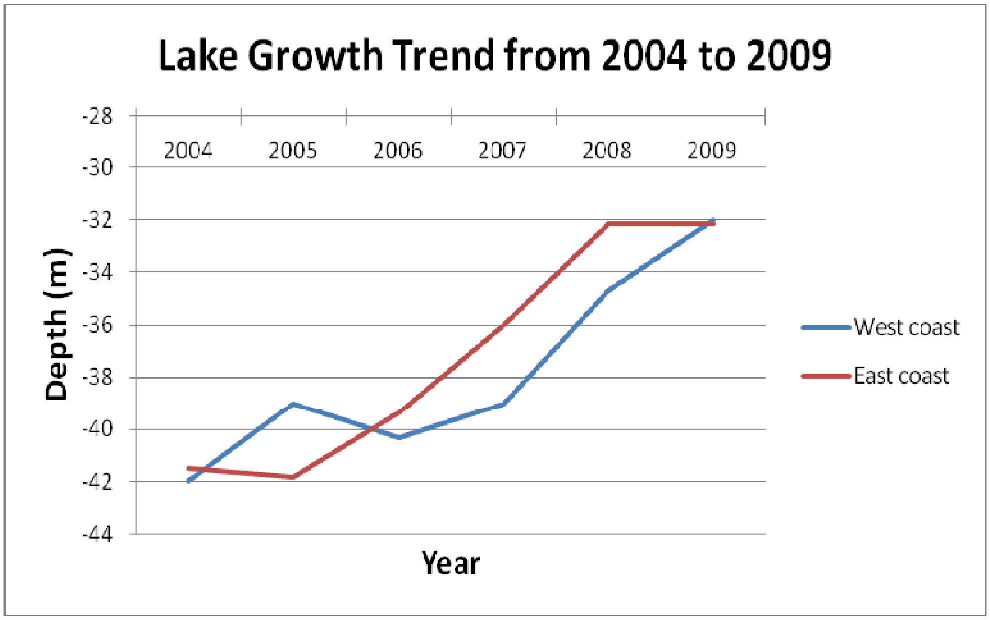
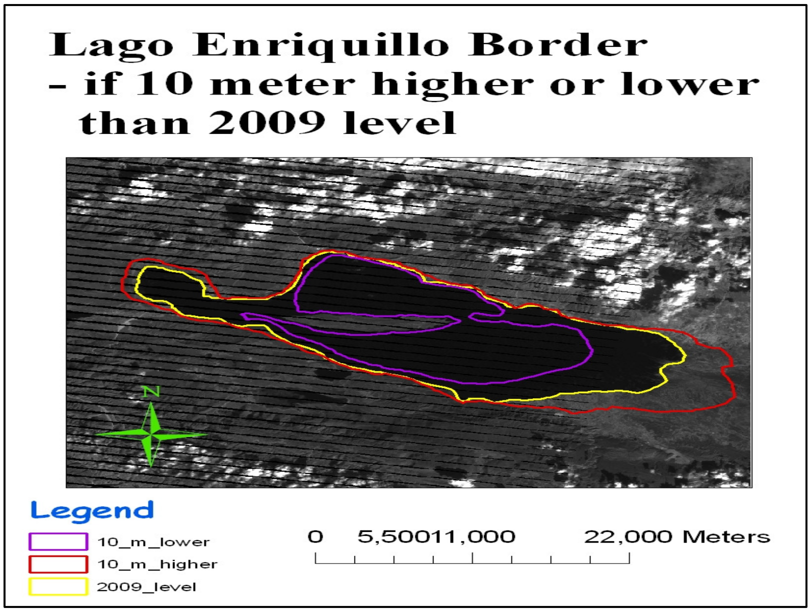


Figure 12: Lake Growth as elevation, it grows around 10 meters on both coasts.

Also using the DEM, we derived a map10 meters below and above the lake level of Lago Enriquillo at the end of 2009, and also one map of both Lago Enriquillo and Lake Sumatre if the water level is 10 meters above the 2009 level. The following maps are created as a reference and warning for the residents; as they shows about where the lakes would reach if they are 10 meter above the 2009 level.

13a)



13b)

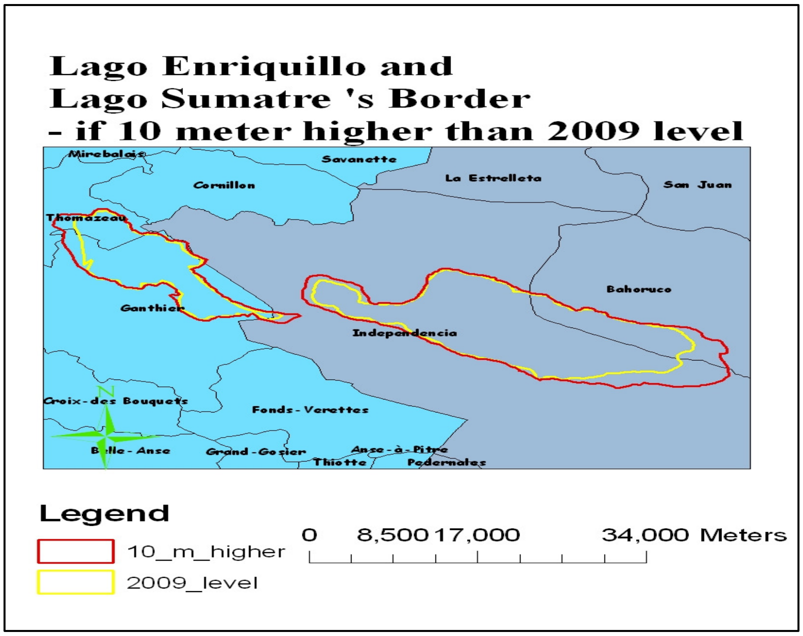


Figure 13: a) Border of Lago Enriquillo if it is 10 meter below or above the 2009 level. b): Border of Lago Enriquillo and Lake Sumatre if water level is 10 meter above the 2009 level.

iii. Annual Variation

It is also important to learn the annual variation of the lake (Lago Enriquillo)'s size. Two years taken to study these variations are 1986 and 2001 since they have more non-cloud data images than other years. Years 2006 to 2009 also have many data images but are not used since there were many hurricane events throughout the year which can vary the usual variation. Below, Figure 13 shows the annual variation of lake area for 1986 and 2001. They are both biggest at the beginning of the year. They then go through a decreasing period and increase again around day 258 in Julian time, which puts the event in mid-September (this matches the late raining period of the region).

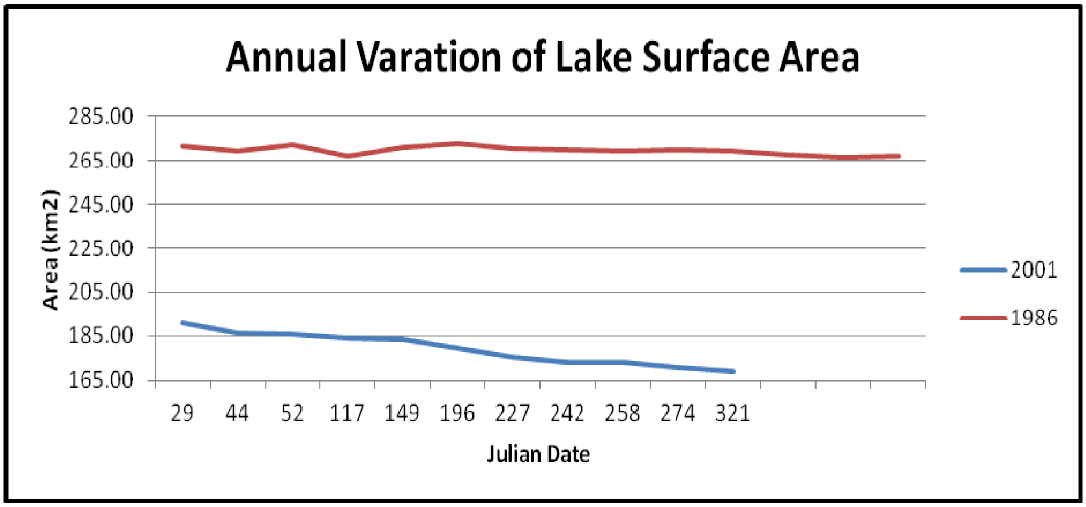


Figure 13: Annual variation of Lago Enriquillo's surface area for 1986 and 2001.

Since 1986 has more complete dataset, one comparison of precipitation and lake surface area is done to check the trend of both factors. Figure 14 is a plot of surface area of the lake at1986 and the daily precipitation of the area (average of Barhona and Santo Domingo weather stations from NCDC). It shows a common peak around May and June for ERS, and peak around September and October for LRS.

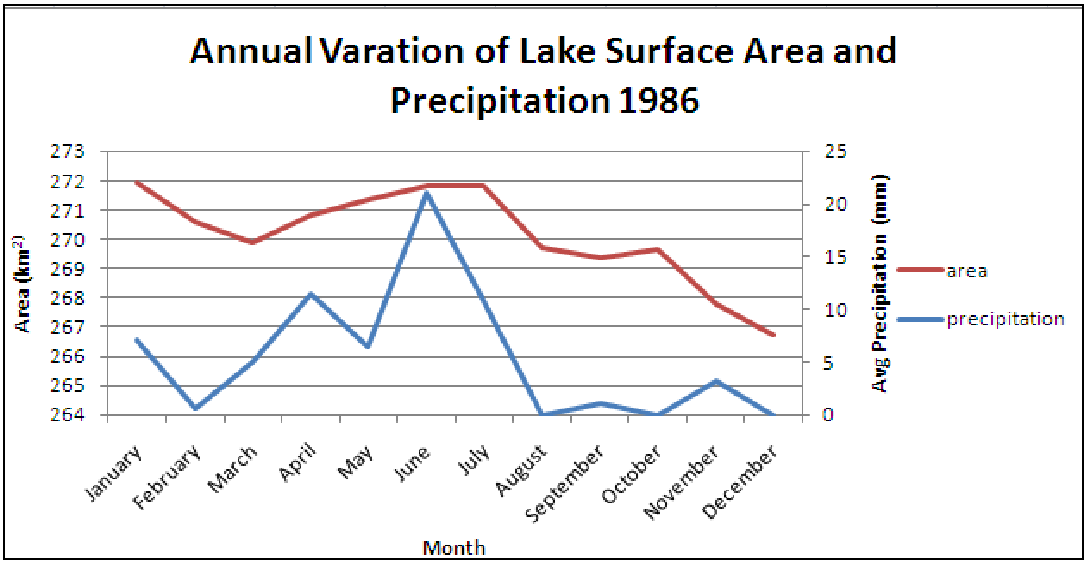


Figure 14: Comparison of precipitation and surface area trend for 1986

iv. Hurricane Case Studies

Three hurricanes—Georges from 1998, Noel from 2007, and Fay from 2008—are picked to evaluate the impact of the rainfall from hurricane to the lake's size. Hurricane Georges crossed the island September 22-23, 1998. The impact to the environment was severe, unfortunately there was no exact precipitation data found for this hurricane. However, Landsat images from September 2nd and October 4th of same year captured the affect of hurricane to the land size.

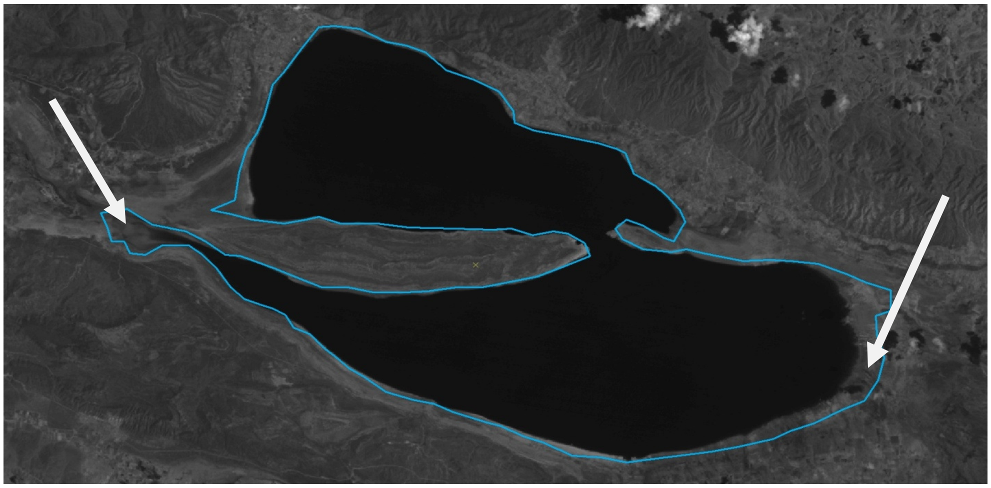


Figure 15: Surface area change by Hurricane Georges 1998.

The blue line is the border of the lake approximately 10 days after hurricane Georges. The base map is the image of the lake on September 2nd. Georges brought an excess amount of rainfall which caused an estimate of 7.7 km^2 increased in surface area. The expansion of the lake as rainfall increased is toward the western and southeastern portion of the lake as shown by arrows on Figure 15—matching the trend previously described.

Hurricane Noel crossed the island September 28-29, 2007. The Landsat images used to evaluate Noel are from September 19th and October 21st 2007. The precipitation brought by the hurricane is recorded to be 25.57 inches at Barahona station from the National Hurricane Center [2]. The surface area change due to the hurricane is estimated by using the area measurement tool in ArcGIS; it is estimated to be around 7.7 km^2. Figure 16 shows before and after hurricane Noel. The base map is the image from September 19th and the blue line is the border on October 21st. The expansion related to hurricane Noel is not as obvious as the impact of hurricane Georges due to the area of lake already being larger by 2007. However, the expansion can still be observed by the extension of the borderline, particularly on the southeastern side, as shown by the arrow.

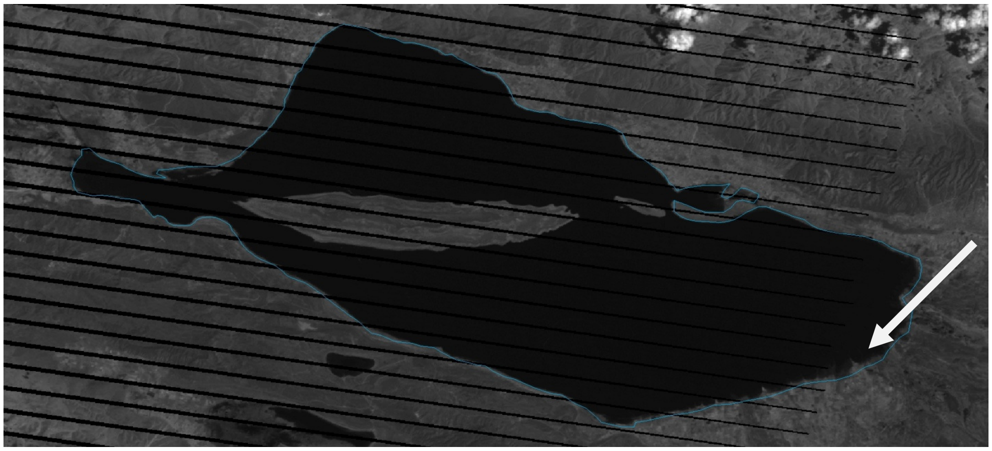


Figure 16: Surface area change by Hurricane Noel 2007.

Figure 17 shows the surface area changes by hurricane Fay from August 15-16, 2008. The base image is Landsat on August 4th and border line is the derived from Landsat on August 20th. The changed is not obvious as the area of the lake is even larger than 2007. The amount of precipitation brought by Fay is about 13.94 inches at Azua station from the National Hurricane Center. The estimated area change is about 5.5 km^2. The changes are not very clear on the map due to the lake size.

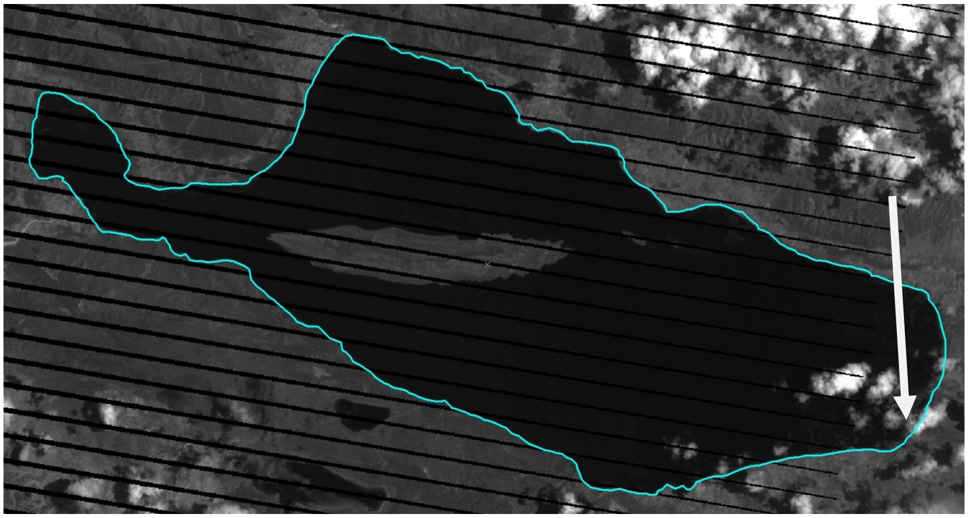


Figure 17: Surface area change by Hurricane Fay 2008.

V: Volume estimation

The volume of the lake is estimated using the lake depth at 2005 as reference (figure 1). Then use DEM to find elevation of lake at 2005, set this as reference, and find any other year's depth by using the elevation difference of that year and 2005. Volume is calculated by depth time the area of the lake. And the area of lake is measured using ArcGIS measurement tool. Table 6 is one year of volume calculation which used for the simple model for this project, and Table 7 is volume estimation for 2004 to 2009 using same method.

Table 6: Estimated volume of Lago Enriquillo at 1986

Year	Month	Day	Area (km2)	Volume (km3)
1986	1	20	269.22	3.35
1986	2	5	272.39	3.39
1986	2	21	267.34	3.33
1986	3	9	270.82	3.37
1986	4	10	273.01	3.39
1986	4	26	270.65	3.36
1986	7	15	269.74	3.36
1986	7	31	269.39	2.94
1986	9	1	270.07	2.94
1986	9	17	269.21	2.93
1986	10	3	267.79	2.92
1986	10	19	266.54	2.91
1986	11	4	266.98	2.91
1986	12	22	268.28	2.92

Table 7: Estimated volume of Lago Enriquillo at 2004 to 2009

Cont'

Year	Month	Day	Area (km2)	Volume (km3)
2004	1	30	176.34	2.47
2004	4	3	174.04	2.44
2004	5	5	173.99	2.44
2004	6	6	169.57	2.39
2004	7	24	175.96	2.46
2004	8	9	177.90	2.48
2004	8	25	179.45	2.50
2004	9	26	178.53	2.49
2004	10	12	223.65	2.55
2004	11	13	231.07	2.63
2004	11	29	232.15	2.65
2004	12	15	233.84	2.67
2005	1	16	237.48	2.78
2005	3	21	239.61	2.81
2005	4	6	238.06	2.79
2005	5	24	240.28	2.81
2005	7	11	246.12	2.88
2005	7	27	247.03	2.89
2005	8	12	250.04	2.93
2005	9	13	253.27	2.97
2005	10	31	252.19	2.95
2005	11	16	250.12	2.93
2005	12	2	254.22	2.98
2006	1	3	252.09	3.01
2006	3	8	254.55	3.04
2006	3	24	256.42	3.06
2006	4	9	255.14	3.04
2006	5	11	256.96	3.06
2006	8	15	255.67	3.05
2006	9	16	260.92	3.11
2006	10	2	272.72	3.25
2006	11	3	280.67	3.35
2006	11	19	285.67	3.41
2006	12	5	295.06	3.52
2007	1	22	298.74	3.72
2007	2	7	302.00	3.76
2007	3	11	305.13	3.80
2007	4	12	306.72	3.82
2007	4	28	304.01	3.78
2007	8	2	305.14	3.80
2007	9	3	303.31	3.78
2007	9	11	306.10	3.81
2007	9	19	315.51	3.93
2007	10	21	323.22	4.02
2007	11	22	327.78	4.08
2007	12	8	327.43	4.08
2007	12	24	331.35	4.13
2008	1	9	333.69	4.30
2008	1	25	334.02	4.30
2008	2	10	330.45	4.25
2008	5	16	334.49	4.31
2008	8	4	329.07	4.24
2008	8	20	334.58	4.31
2008	9	5	331.05	4.26
2008	9	21	334.40	4.31
2008	10	23	335.76	4.32
2008	11	24	328.47	4.23
2008	12	26	330.59	4.26
2009	1	11	328.73	4.40
2009	2	28	332.56	4.46
2009	4	17	343.97	4.61
2009	5	3	333.21	4.47
2009	5	19	330.07	4.42
2009	7	6	329.07	4.41
2009	8	7	334.58	4.48
2009	8	23	331.05	4.44
2009	9	8	334.40	4.48
2009	9	24	335.76	4.50
2009	10	10	328.47	4.40
2009	10	26	330.59	4.43
2009	11	11	328.73	4.40
2009	12	29	332.56	4.46

VI: Similar growth pattern Lago Enriquillo and Lake Sumatre from 1996 to 2009

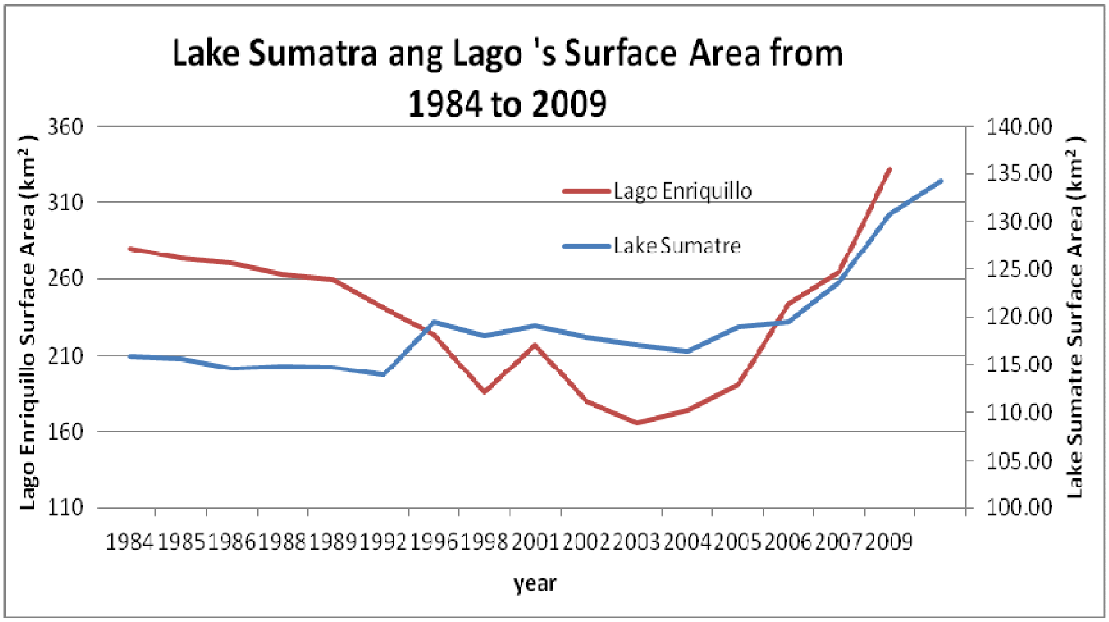


Figure 18: Similar growth pattern of Lago Enriquillo and Lake Sumatre from 1996 to 2009.

Since 1996, both lake exhibit the similar growth pattern; decreased in 1997, increased to 2001, then decreased again to 2003 and 2004, and then continue to grow until now.

b) Karsha Walker

i. Precipitation Analysis

Over the past years, there have been reports of a significant increase in size of the Lago Enriquillo which have resulted in floods and loss of agricultural and pastoral land. The lake has no known inflow other than surface runoff and the only source of outflow is evaporation. Dominican Republic has experienced increased rainfall in the past years and also the number of hurricanes in the Caribbean region of Dominican Republic has increased in both number and strength; this has also resulted in increased precipitation over the island. These changes show a strong representation of changes associated with climate changes events which can also result in changes in weather patterns in the region of the Caribbean. In this section a 30-year, 1979-2009, analysis of precipitation and extreme events in region of Lago Enriquillo is presented to determine correlation between the changes in the size of the lake and changes in the climatology- precipitation of the region.

The dataset was retrieved from the National Climatology Data Center – Climate Data Online system (NCDC-CDO) website that is operated by the National Ocean and Atmosphere Administration (NOAA). The data summaries are based on data exchanged under the World Meteorological Organization (WMO). There are 13 active stations located on the island. Table 8 shows the six stations used for this project which Figure 19 shows the locations of the selected stations and others.

Table 8- NCDC Station in Dominican Republic from which data was acquired.

USAF WBAN ID	Station Name	Period of Data	Latitude	Longitude	Distance to lake (km)
784820 99999	BARAHONA	1979-2010	18.21667	-71.33333	48.326
784600 99999	SANTIAGO	1979-2010	19.5	-70.66667	140.68
784570 99999	PUERTO PLATA INTL	1979-2010	19.75778	-70.57	168.94
784860 99999	SANTO DOMINGO	1979-2010	18.53333	-71.96667	180.23
784780 99999	CABO ENGANO	1979-1991	18.61667	-69.31667	237.45
784790 99999	PUNTA CANA	1993-2010	18.567	-68.367	339.38

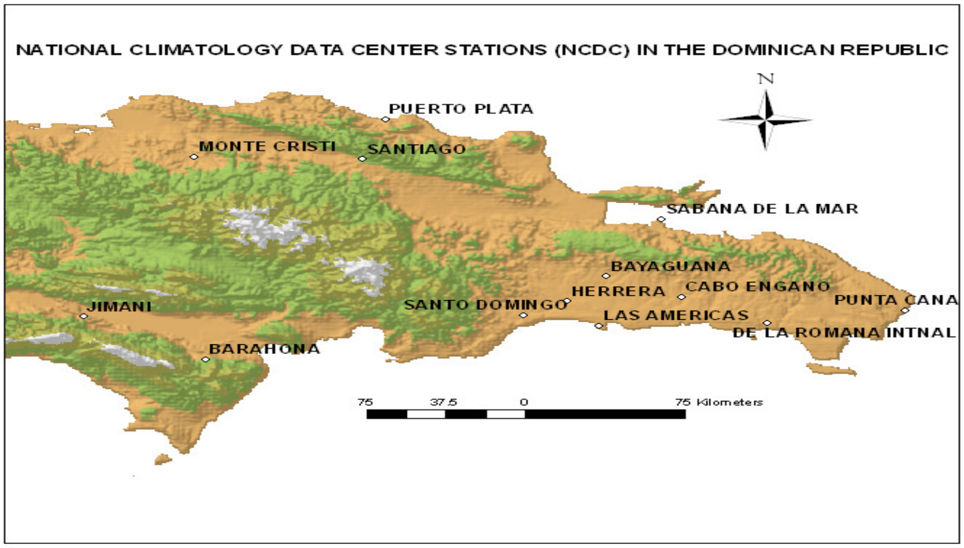


Figure 19: Map of Dominican Republic showing location of NCDC stations.

The main precipitation dataset used this project are obtained from the Barahona and Santo Domingo. The Barahona station is located at 18° 13'N and 71° 19'W which is 48.326 km south- east of the Lago Enriquillo which is located at 18° 30'N and 71° 35'W. The Santo Domingo station is located at 18° 31'N and 71° 58'W which is 180.23 km east of Lago Enriquillo. The Santo Domingo station was used as the data received from Barahona was incomplete and inconsistent had large periods of data been missing. There was no data recorded after April 1996 to December 1998. The precipitation data was recorded hourly for time period of 3-hours, 6-hours, and 24-hours. The final precipitation data used for the analysis was the 24-hours value and for records that had no available 24-hours values, the sum of the available 3-hours and the 6-hours records were used.

Regional Precipitation Analysis

In conducting a regional analysis of the precipitation of the island, the six stations listed in table 8 was used. Based on the geography of the island, the locations of the stations and quantity of data available, the southern region is represented by Barahona and Santo Domingo, the northern region is represented by Puerto Plata International airport and Santiago, the eastern region is represented by Punta Cana and Cabo Engano.

The daily accumulation per year for each station is plotted in Figure 20. The average precipitation for the region is 774.08 mm of rainfall per year. The average rainfall for the southern region is 856. 57 mm per year while in the northern region is 812.21 mm per year. Based on the data the station with the highest yearly average of rainfall is Santo Domingo with an average of 1070.32 mm per year. In the region closes to the lake, Barahona, the average rainfall per year was determined to be 642.82 mm.

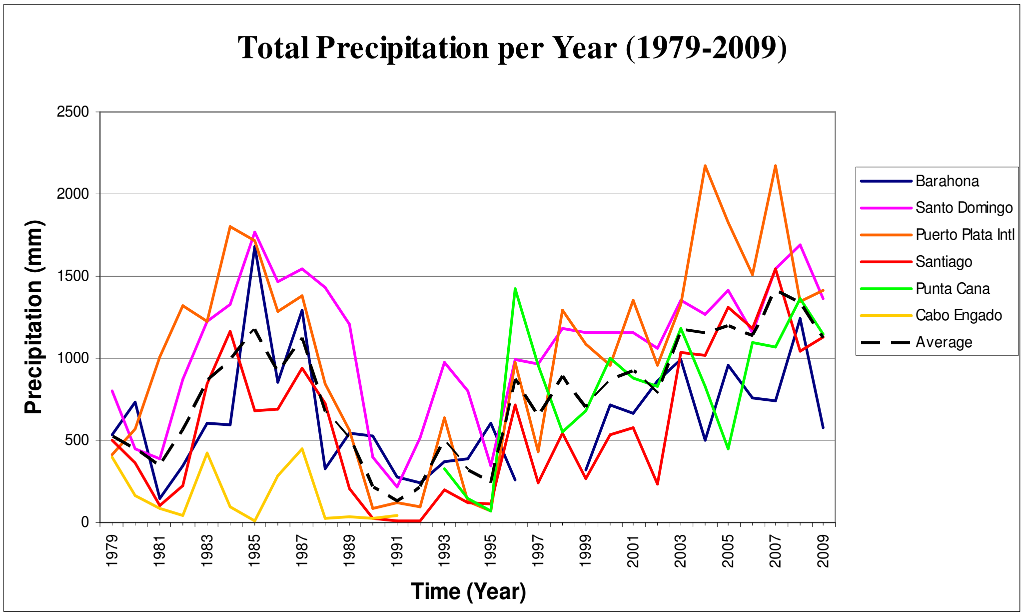


Figure 20: Regional 30-year daily –accumulated precipitation by 6 stations.

The overall precipitation increase since 1979 to 2009 has been approximately 50% with highest regional average rainfall of one year occurring in 2006, 1415 mm, which shows a 62% increase since 1980 to 2006.

By further analysis of the average rainfall of the region, Figure 21 shows a linear increase in average precipitation, with an R-squared factor of 0.8478.

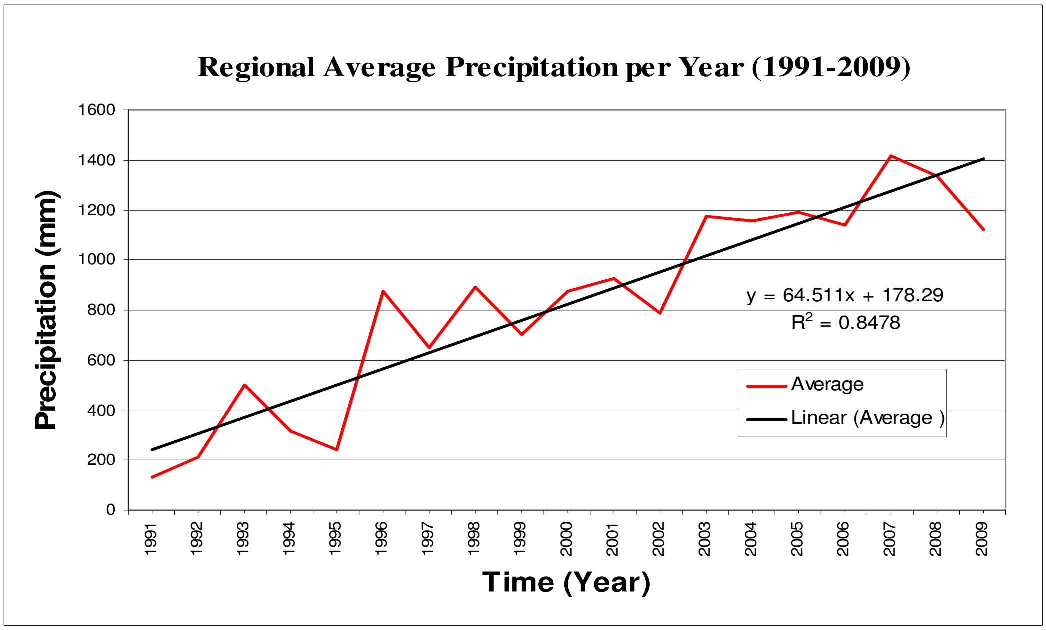


Figure 21: Regional average rainfall per year for 1991 to 2009 showing linear increase in rainfall.

Local Precipitation Analysis

The regional precipitation trend has been established, the local precipitation of the region around the lake is being focused on. The Lago Enriquillo is located in the Hoya Lago Enriquillo (hoya translate to mean a valley or trench) between two distinct mountain ranges; the Sierra de Neiba mountain to the north of the lake and the Sierra de Baoruco mountain ranges the south of the lake.

In conducting a 30-year precipitation analysis for the local region of the lake, Figure 22 shows the overall total precipitation per year for two stations, Barahona and Santo Domingo, and the average rainfall of the combined stations per year. For both stations, 1985 had the highest rainfall amount of with an average of 1723.54 mm for the year. Overall, since 1979 to 2009, precipitation amount has increased by approximately 30%.

By focusing on separate 10 year periods, the result the breakdown of the average total precipitation for the two stations (Figure 22 black dash line) shows average rainfall:

- 1980-1989: 945.88 mm
- 1990-1999: 701.34 mm
- 2000-2009: 1056.89 mm

In comparison to the 1980 -1989 period, rainfall average of the 1990-1999 period decreased by 25% whiles the 2000-2009 period increase by 10%. And in comparison to the 1990-1999 period, rainfall average of the 2000-2009 periods increase by 33%. Based on these results, during the 2000-2009 period represents an overall steady increase of rainfall with more years with higher amounts of precipitation compared to the previous periods.

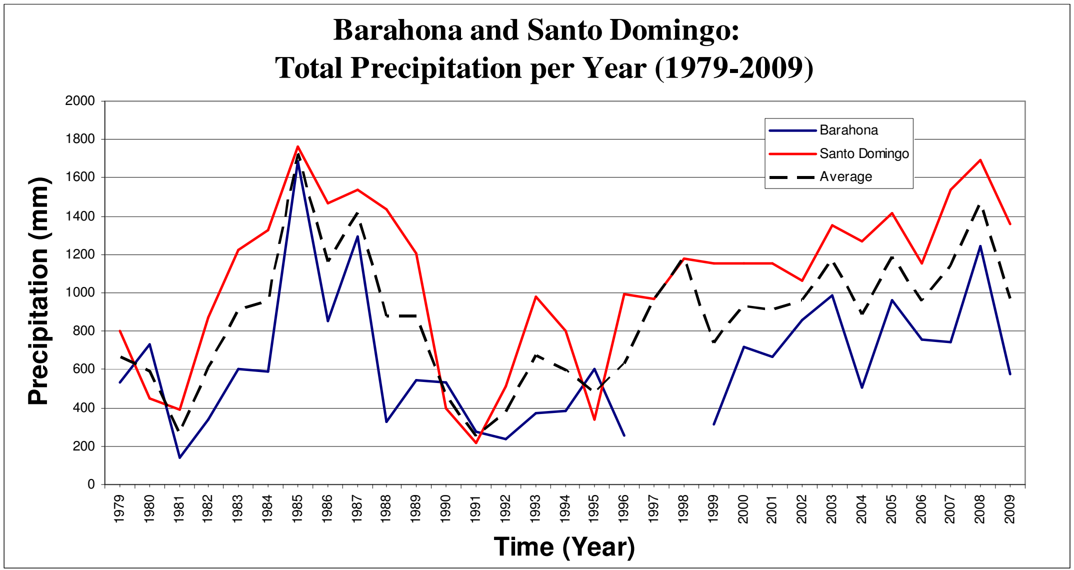
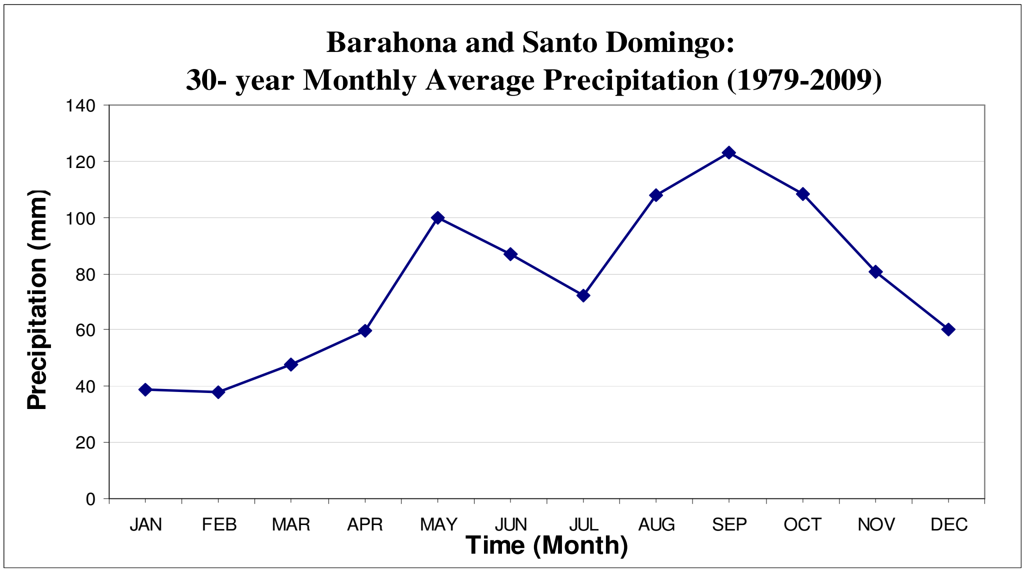


Figure 22: Local Precipitation: Barahona and Santo Domingo Total Precipitation, 1979-2009.

The island and the Caribbean experiences two distinctive weather seasons, a dry season and a bimodal rainfall season. The dry season extends from December to March. The rainfall season is classified by the early and late rainfall season. The early rainfall season extends from May to June with a brief dry period in July and the late rainfall season extend from August to November with peak rainfall in October. By analysis the 30-year monthly averages, as shown in Figure 23a, it can be determine if there are any changes in rainfall patterns in the region of the lake as this could also be a factor of the changes in the size of the lake. And to verify the data, Figure 23b shows the 30-year monthly averages comparison with that of Puerto Rico (Comarazamy and González)

a)



b)

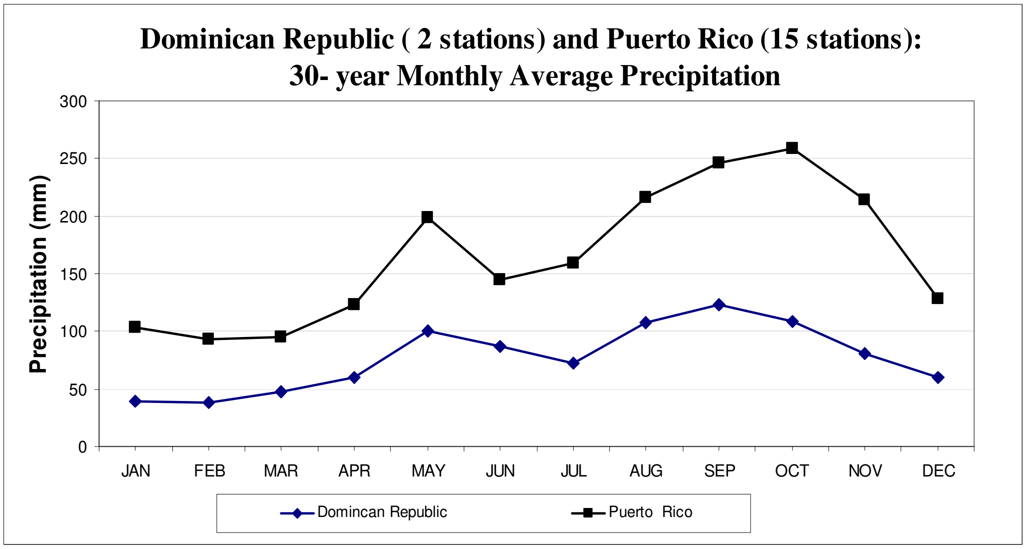


Figure 23: **a)** Barahona and Santo Domingo 30-year monthly averages, 1979-2009. **b)** Data validation using Puerto Rico 30-year monthly averages.

Based on Figure 23a, the data corresponds with the expected weather season of the region. The results of a regression analysis for the data of Figure 23b is presented in Table 9 and Figure 24.

Table 9: Regression Statistics- monthly averages for Dominican Rep. and Puerto Rico

Dominican Rep. and Puerto Rico Regression Statistics	
Multiple R	0.93
R Square	0.86
Adjusted R Square	0.84
Standard Error	10.95
Observations	11

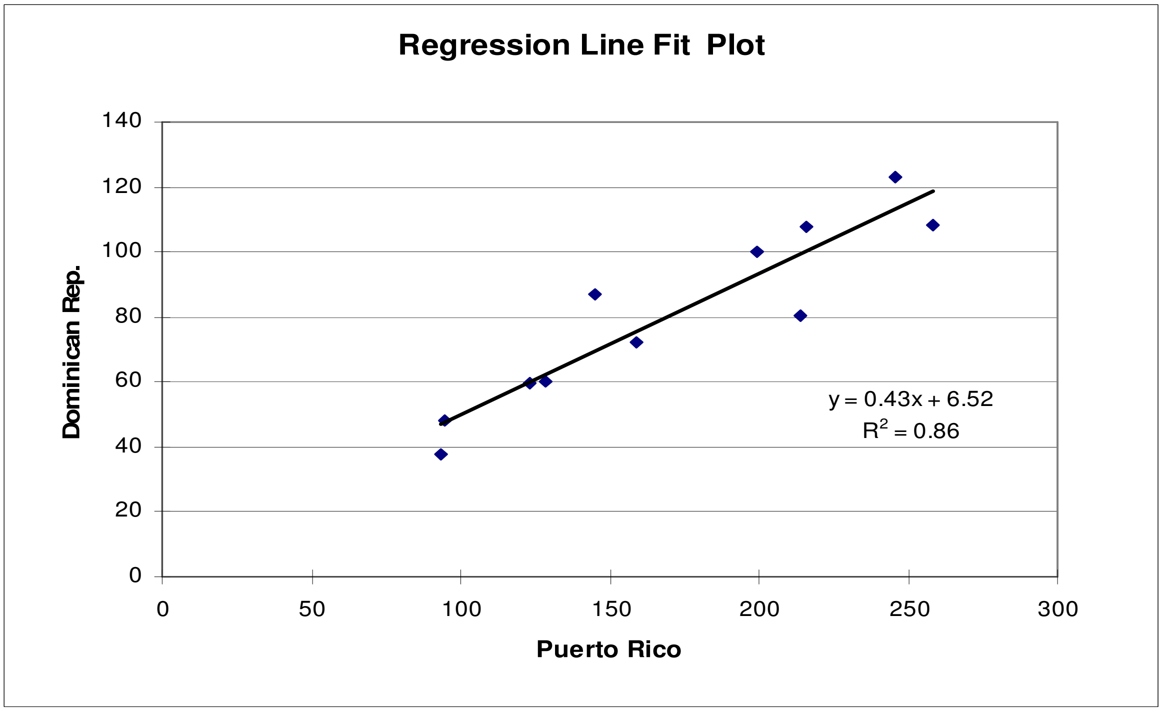


Figure 24: Regression Analysis- Line Fit plot Puerto Rico vs. Dominican Republic

In order to identify specific monthly averages and changes in seasonal variation of the region, the data is analysis based on the three 10 year periods which is shown in Figure 25 and seasonal variations shown in Figure 26.

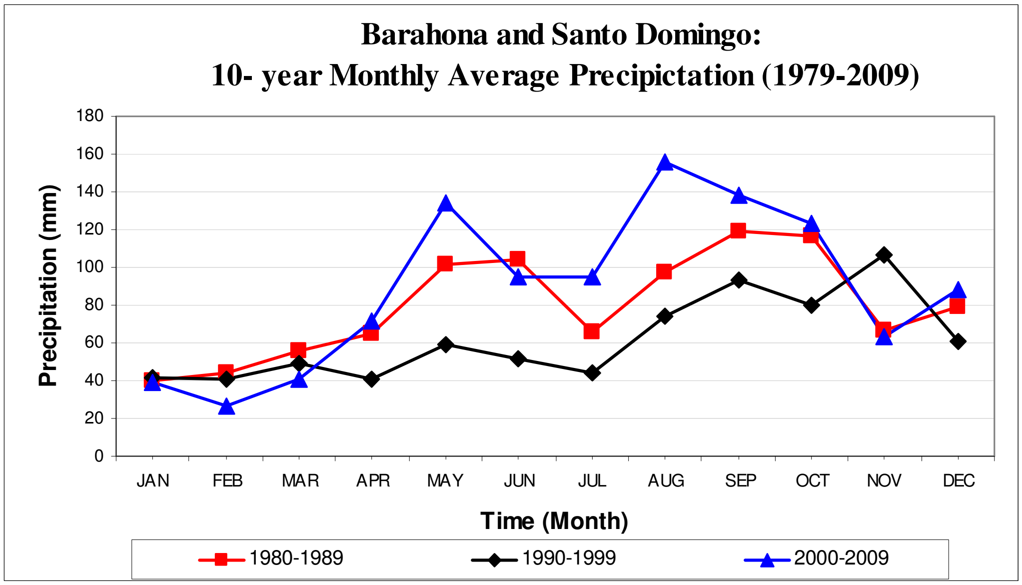


Figure 25: 10-year precipitation monthly averages for Lago Enriquillo region.

Based on Figure 25, the 2000–2009 rainfall years showed the highest variation in monthly rainfall which an overall monthly average of 88.07 mm of rainfall. While the 1990-1999 rainfall period showed the lowest average with 60.58 mm rainfall. Based on Figure 8, the seasonal variation of the region has remained with in the expected weather variation. However, the graph shows a 10% and 16% increase in early and late fall season, respectively, between 1980-1989 and 2000-2009 period and 15% decrease in rainfall for dry season between 1980-1989 and 2000-2009 periods.

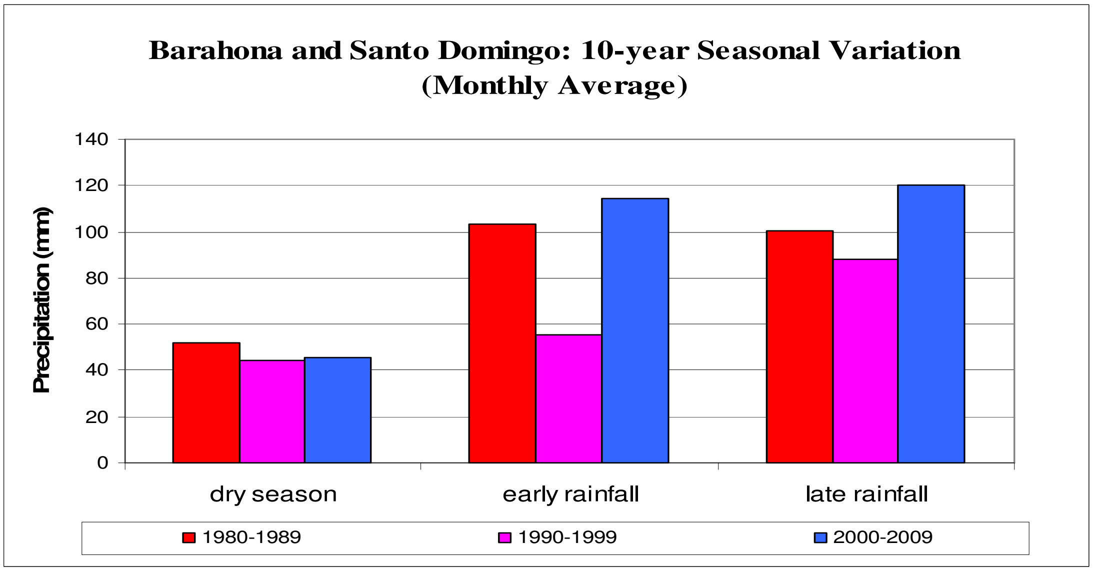


Figure 26: Barahona and Santo Domingo Seasonal Variation Patterns, 1980-2009

ii. Statistical Analysis of Precipitation and Lake Surface Area

The following Figure 27 shows the correlation between the changes of lake surface area and the yearly precipitation averages for Barahona and Santo Domingo for 1984 to 2009. The correlation of the change of lake surface area and change of precipitation was calculated to be 0.42.

Table10: Regression Summary- Precipitation vs. Lake Surface area, 1984-2009

Regression Statistics: Precipitation and Lake Surface area, 1984-2009	
Multiple R	0.651292636
R Square	0.424182098
Adjusted R Square	0.400189685
Standard Error	77.27313515
Observations	26

Analysis of Variance (ANOVA)

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	105568.77	105568.77	17.68	0.00
Residual	24	143307.30	5971.14		
Total	25	248876.07			

Intercept Regression Coefficient Table

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	11.35	48.79	0.23	0.82	-89.35	112.06
Precipitation	2.45	0.58	4.20	0.00	1.25	3.65

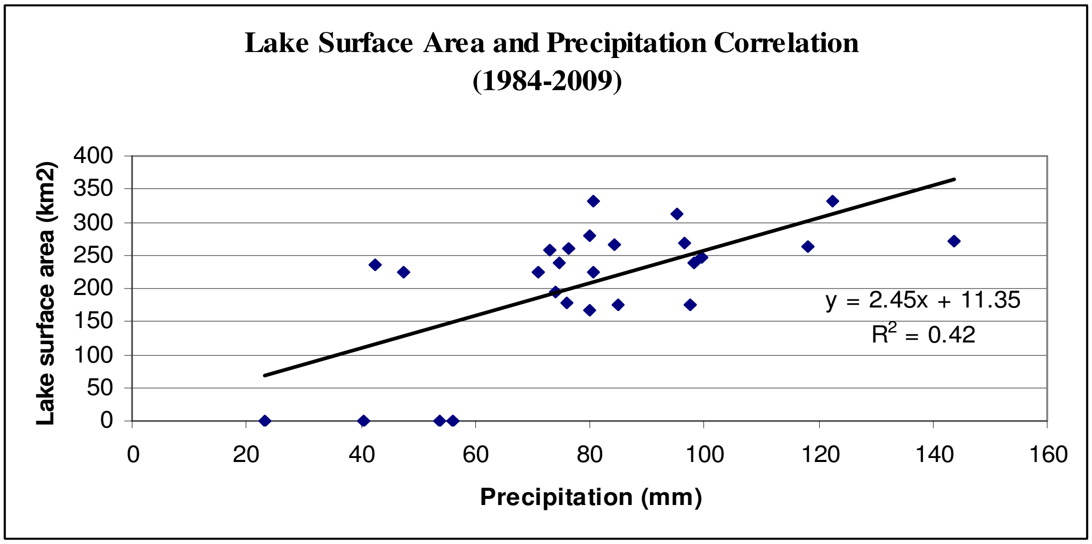


Figure 27: Line Fit Plot- Surface area and Precipitation, 1984-2009

Based on the correlation factor of 0.42, it can be concluded that there is no significant relationship between the two variables. The confidence interval for the slope is (1.25, 3.65).

c) Alvin Molina

i. Surface Temperature Analysis

In order to study the temperature patterns of the region close to the Lago Enriquillo, an analysis of the average temperature over the last 30 years was conducted. The Barahona weather station data was utilized for this analysis. By analyzing the monthly average temperature of the region from 1978 to 2009, it was found that the lowest average temperatures are recorded in the month of January and the highest temperatures are recorded in the month of July, illustrated in Figure 28. This figure also shows that the highest temperatures occur from May to September, which corresponds with the rainy season.

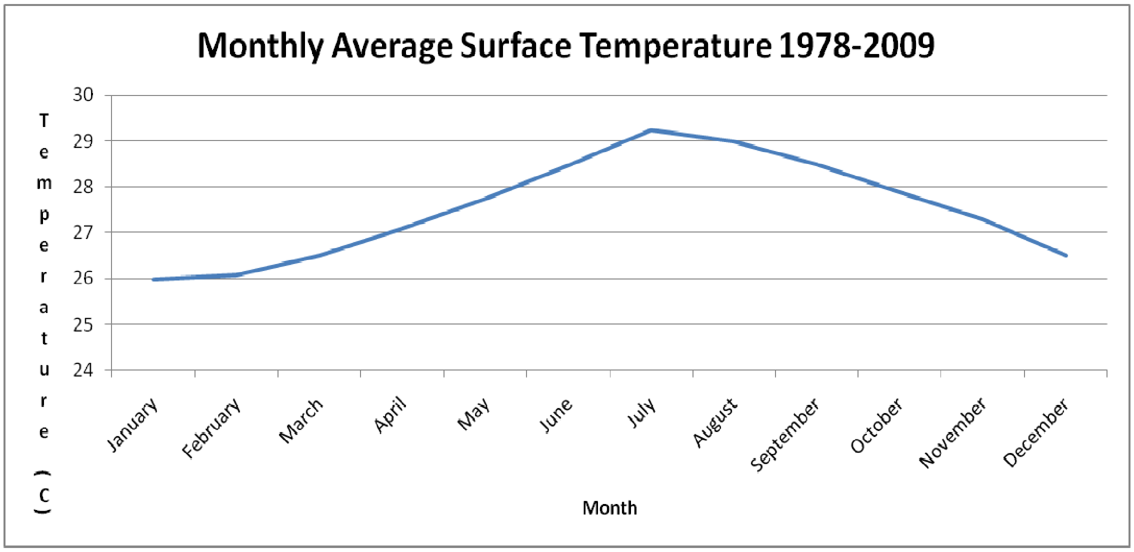


Figure 28: Monthly Average Surface Temperature 1978-2009

The average temperatures of the region have been increasing over the last 30 years as seen in Figure 27. The greatest increase in temperature was recorded during the 2000-2009 period where the average increase was higher than the average increase during 1978-1989.

- Average temperature increase during 1978-1989: **0.03287 degrees Celsius**
- Average temperature increase during 1990-1999: **0.03665 degrees Celsius**
- Average temperature increase during 2000-2009: **0.09206 degrees Celsius**

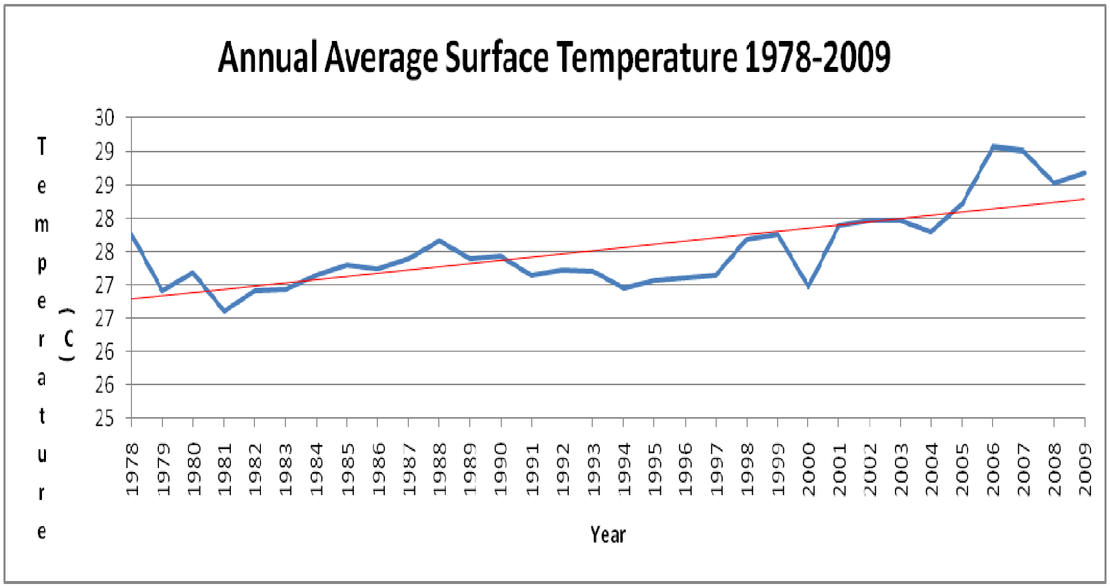


Figure 27 - *Annual Average Surface Temperature 1978-2009*

The following graph shows you the behavior of the temperature during the last 30 years in 10 years span. It is noticeable that the temperature has been increasing since the last decade.

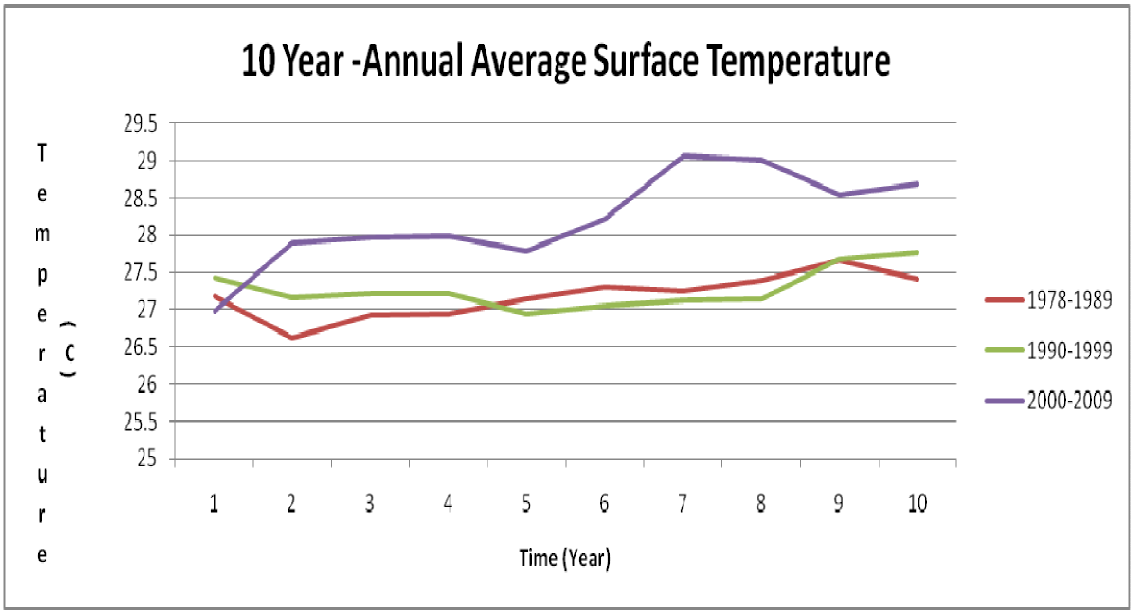


Figure 28 – 10 Year - *Annual Average Surface Temperature*

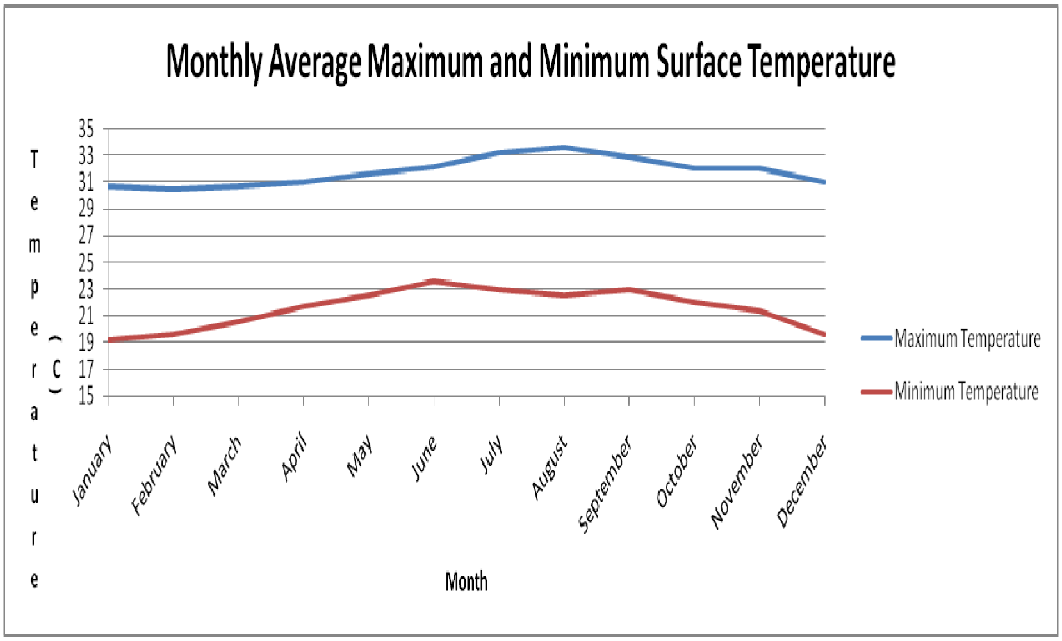


Figure 29 - Monthly *Average Maximum and Minimum Surface Temperature*

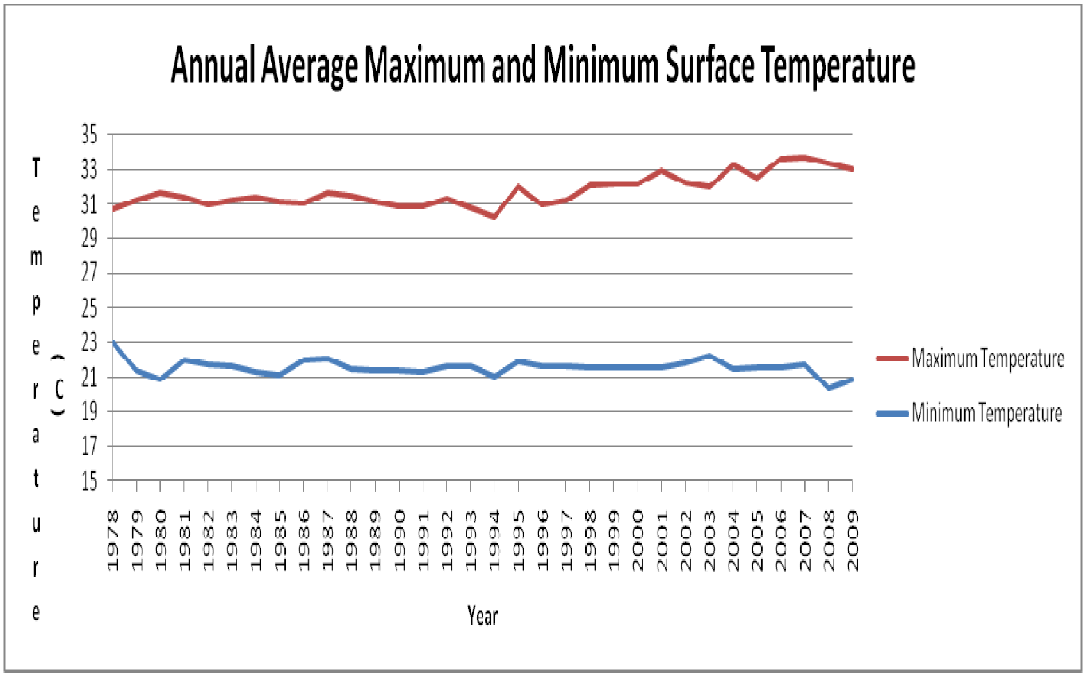


Figure 30 - *Annual Average Maximum and Minimum Surface Temperature 1978-2009*

A comparison of the average temperature change was conducted. The time frames that were evaluated were 1978-1989 and 2000-2009, illustrated in Figure 31. Analysis of the data from those decades shows an increase of **1.01℃** in the average temperature of the region since 1978.

- Average Temperature: 27.21 °C
- Highest Average Temperature: 27.77 °C
- Lowest Average Temperature: 26.62 °C

- Average Temperature: 28.22 °C
- Highest Average Temperature: 29.07 °C
- Lowest Average Temperature: 26.98 °C

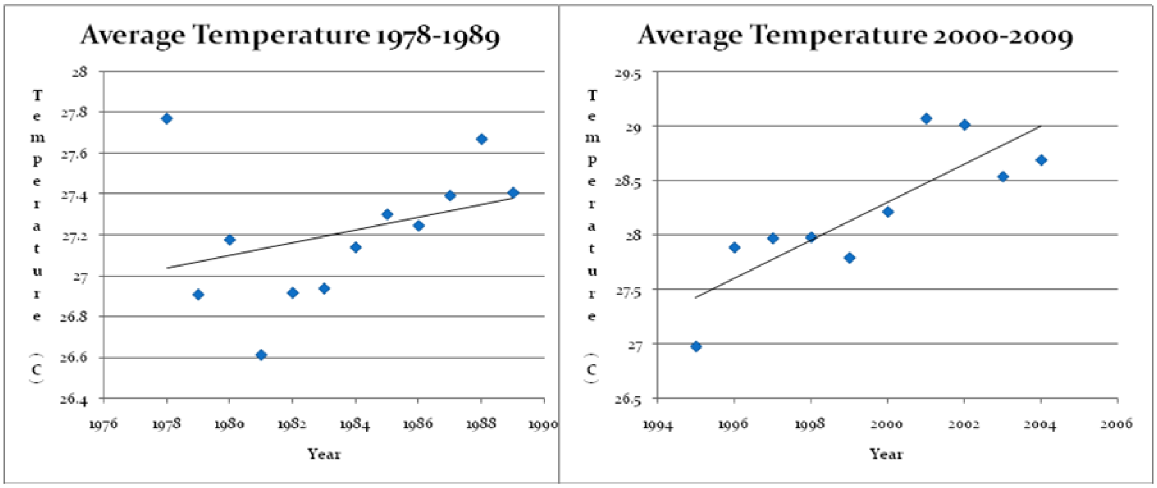


Figure 31 - *Comparison of Averages Surface Temperatures 1978-1989 (left) and 2000-2009 (right)*

The average temperatures of the region close to the Lago Enriquillo have been increasing over the last 30 years. This pattern will likely continue for the next 25 years based on the trending analysis of the temperatures. Figure 32 shows that if the average temperature continues to follow the trend, the increase will be around **1.225 degrees Celsius** by the year 2035.

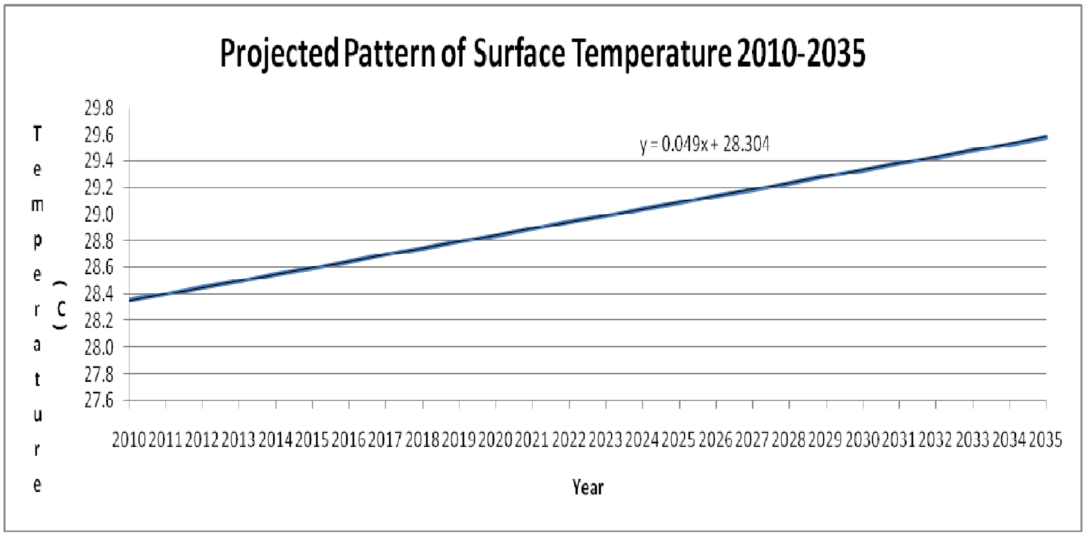


Figure 32*:* Projected Pattern of Average Surface Temperature 2010-2035

The temperature and precipitation of the region have had a similar pattern over the last 30 years, shown in Figure 33. This figure shows that both factors have been experiencing a non-stop increase since 2004.

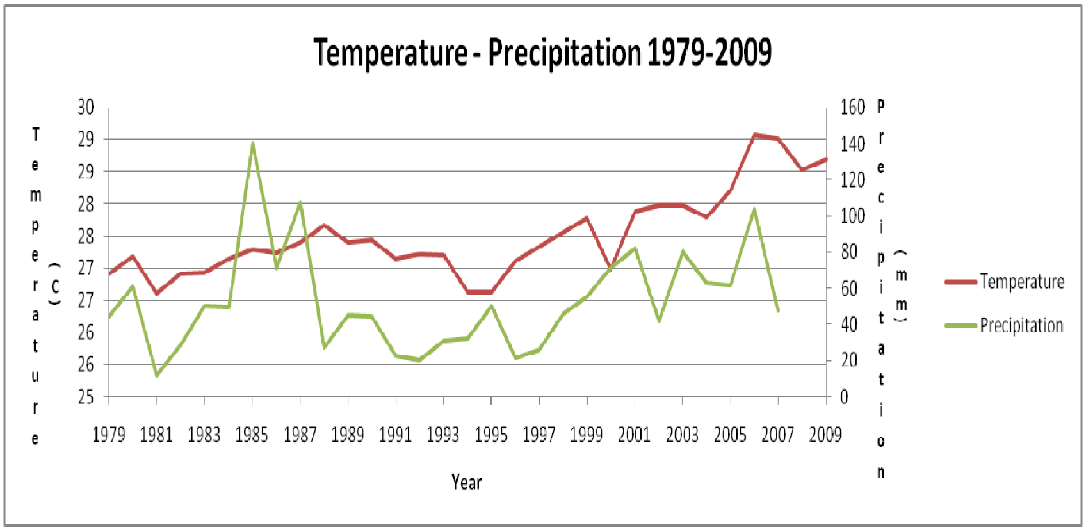


Figure 33 - Temperature – Precipitation Graphs 1978-2009

There is a similar trend observed between the precipitation, temperature, and lake growth illustrated by Figure 34. Around year 2004 is the lowest point for all three factors and after 2004 all three elements begin to increase together.

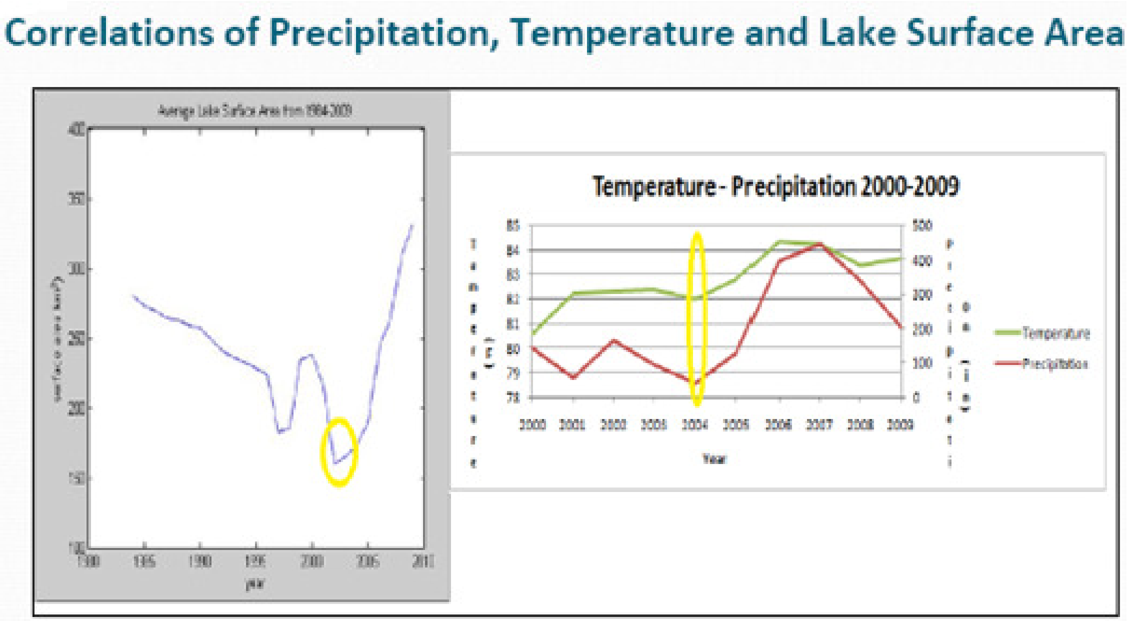


Figure 34: Similarity in trends of precipitation, temperature, and Lake Surface

ii. Sea Surface Temperature Analysis

The average sea surface temperatures for the last 27 years were studied. The averages taken into consideration were the temperatures recorded from latitude 8N to latitude 24N and from longitude 58W to longitude 89W. On this region is where the Hispaniola Island is located. The Reynolds-Smith data from 1982 to 2009 was used for this analysis. As it is shown on figure 35, February is when the lowest average sea surface temperature is recorded. On the other hand, September is when the highest average sea surface temperature is recorded. The highest temperatures occur from late June to late November which corresponds to the hurricane season of the area.

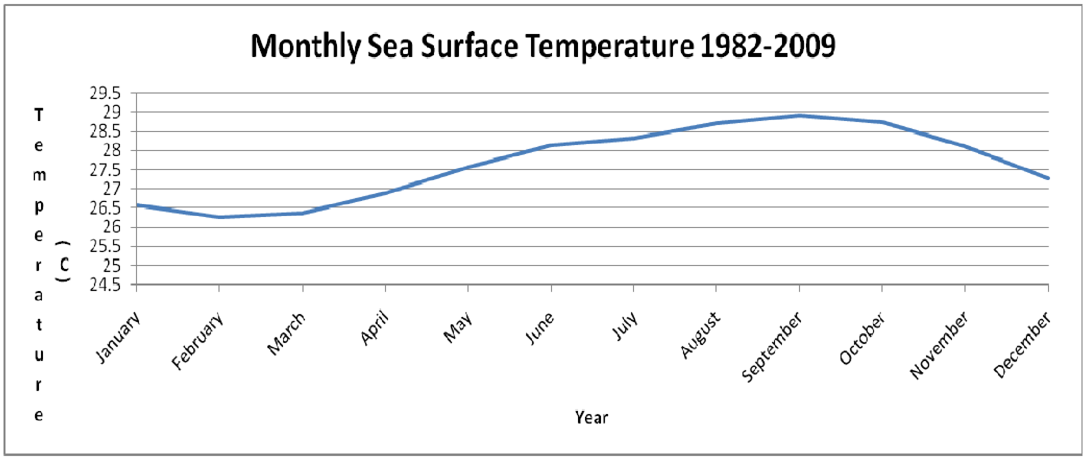


Figure 35 – Monthly Average Sea Surface Temperature 1982-2009

The average sea surface temperatures have been increasing over the last 27 years (1982-2009), as it is shown in Figure 36. The greatest increase in average sea surface temperature was recorded during the 2000-2009 period, where the average increase was higher than the average increase during 1990-1999.

- Average SST increase during 1982-1989: **0.0063 degrees Celsius**
- Average SST increase during 1990-1999: **0.0149 degrees Celsius**
- Average SST increase during 2000-2009: **0.0245 degrees Celsius**

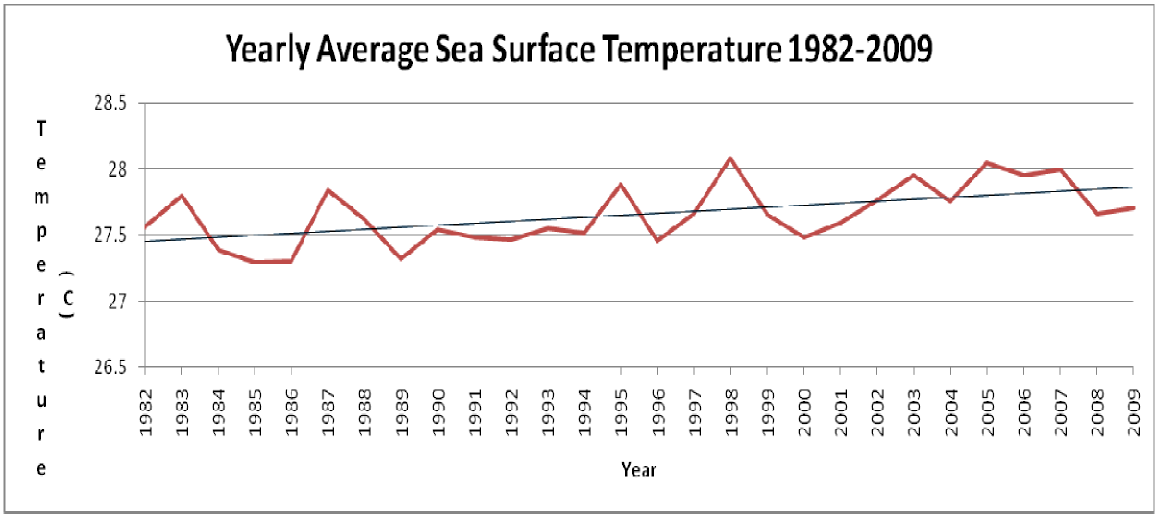


Figure 36 - Annual Average Sea Surface Temperature 1982-2009

The following graph shows you the behavior of the temperature during the last 27 years in 9 years span. It is noticeable that the temperature has been increasing since the last nine years.

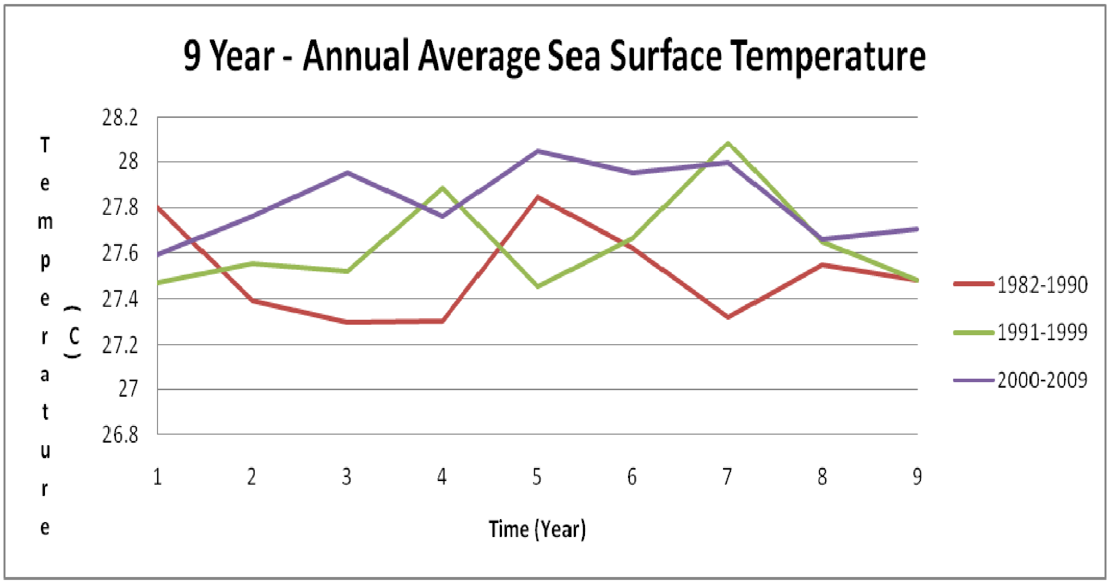


Figure 37 – 9 Year - Annual Average Sea Surface Temperature

A comparison of the average sea surface temperature was conducted. The time frames that were evaluated were 1982-1989, 1990-1999 and 2000-2009, illustrated in Figure 37. The analysis of the data from those time frames shows there has been a slight increase of **0.25℃** in the average temperature of the region over the past 10 years.

A comparison of the average sea surface temperature change was conducted. The time frames that were evaluated were 1982-1989, 1990-1999 and 2000-2009, illustrated in Figure 38 a-c. Analysis of the data from those decades shows an increase of **0.27℃** in the average temperature of the region since 1982.

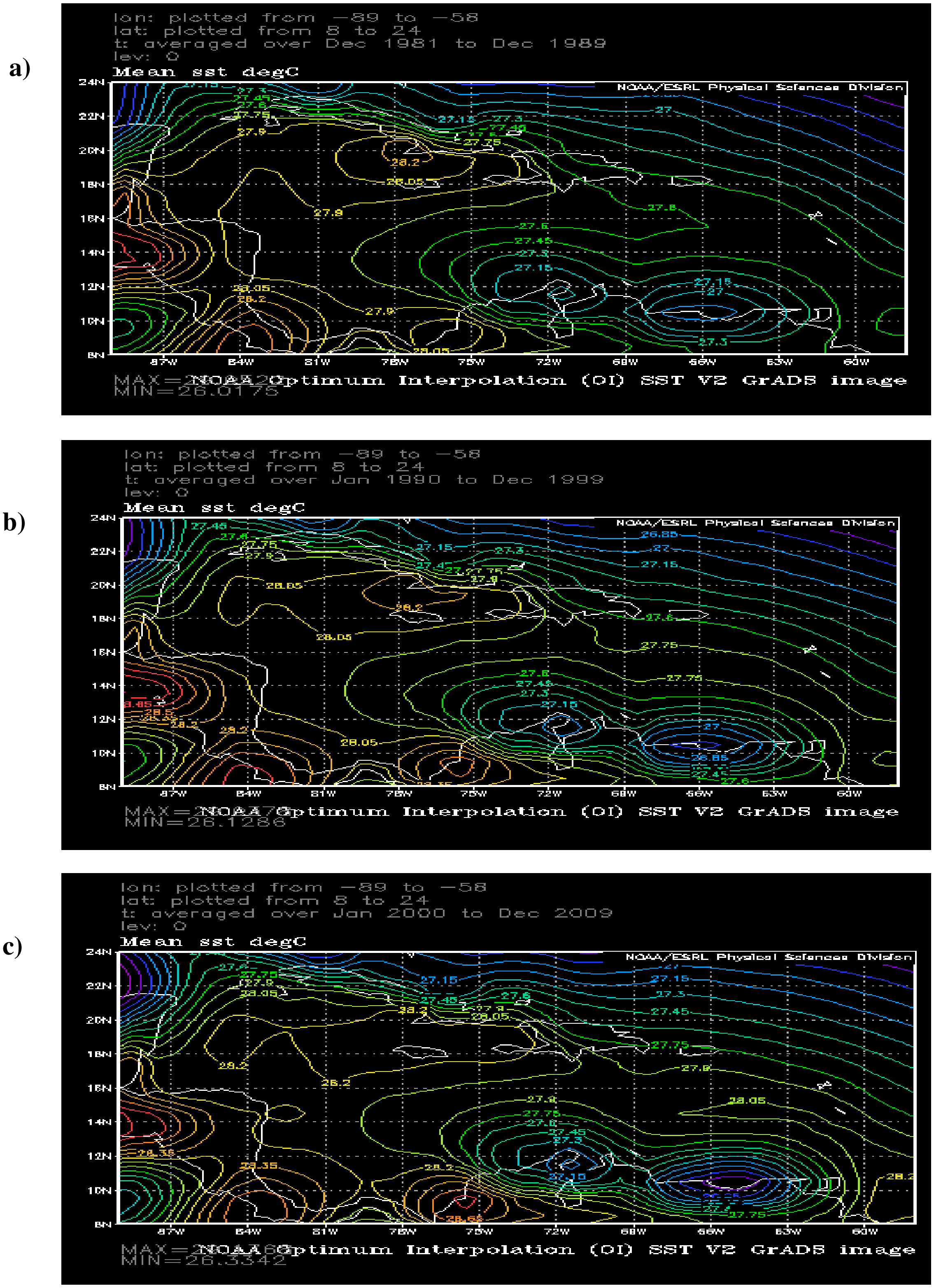


Figure 38 - Projected Pattern of Average Sea Surface Temperature a) 1982-1989 (top), b) 1990-1999 (middle) and c) 2000-2009 (bottom).

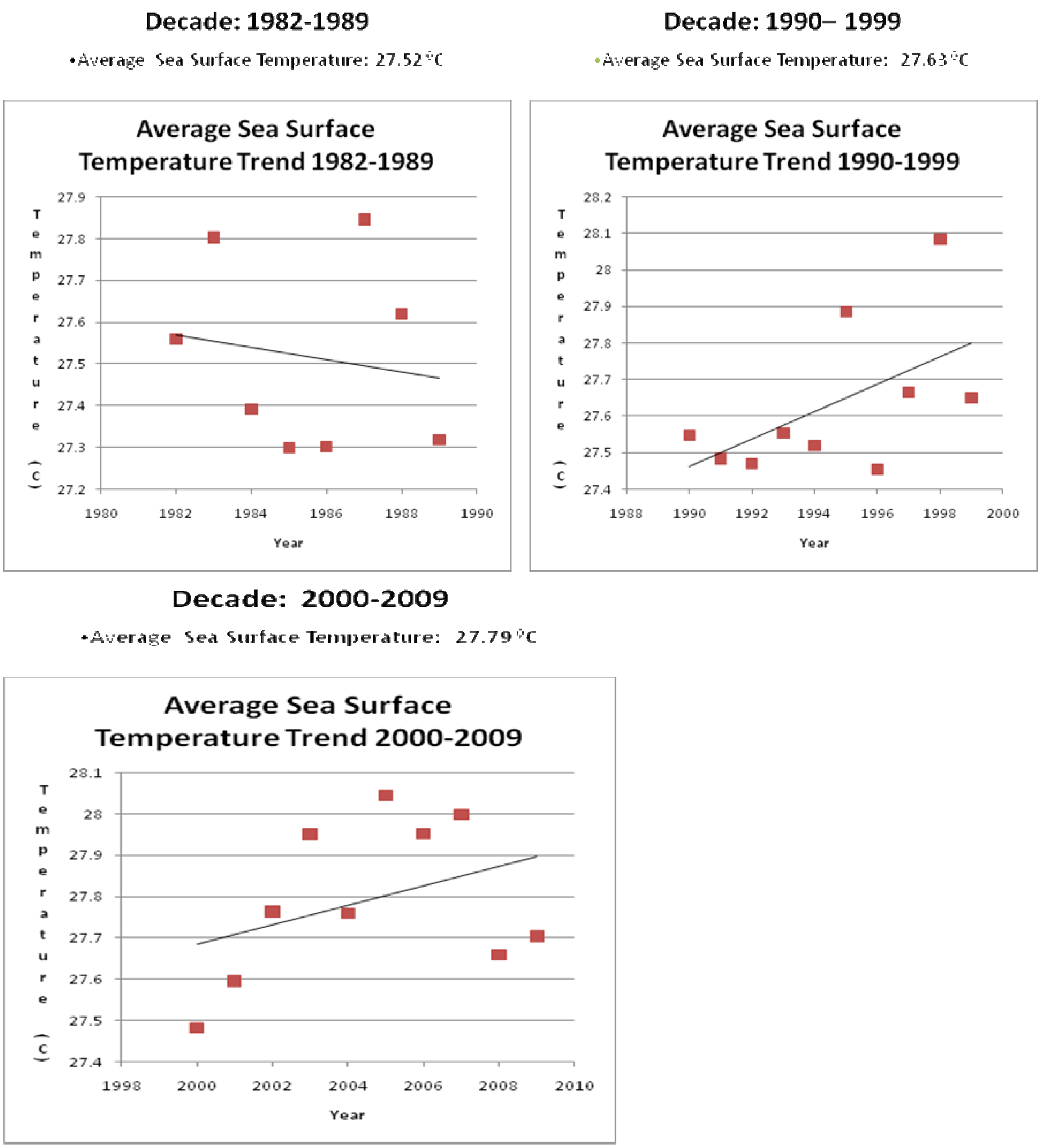


Figure 39 - Comparison of Averages Surface Temperatures since 1982-2009

The average sea surface temperatures around the Hispaniola Island have been increasing over the last 27 years. Based on the trend analysis of, this pattern will likely continue over the next 25 years, as shown in Figure 40.

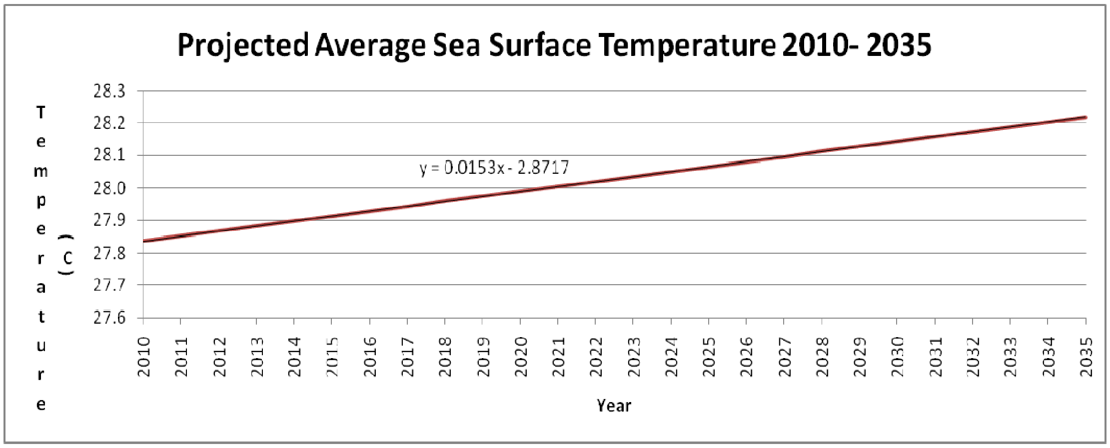


Figure 40 - Projected Pattern of Average Sea Surface Temperature 2010-2035

Figure 41 shows that sea surface temperature and precipitation in the region has had a similar pattern during the last 30 years. It also shows that both factors have been experiencing a non-stop increase since 2004.

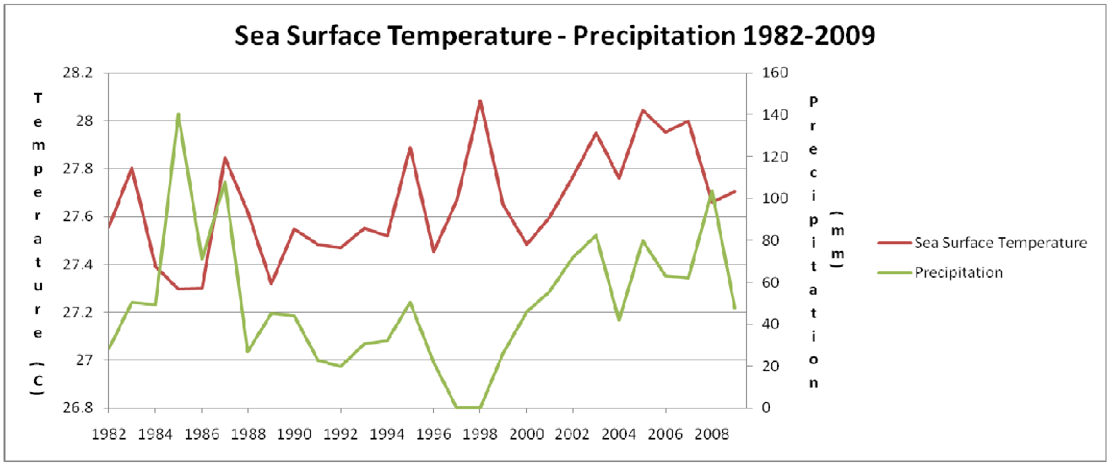


Figure 41 - Sea Surface Temperature – Precipitation Graph 1978-2009

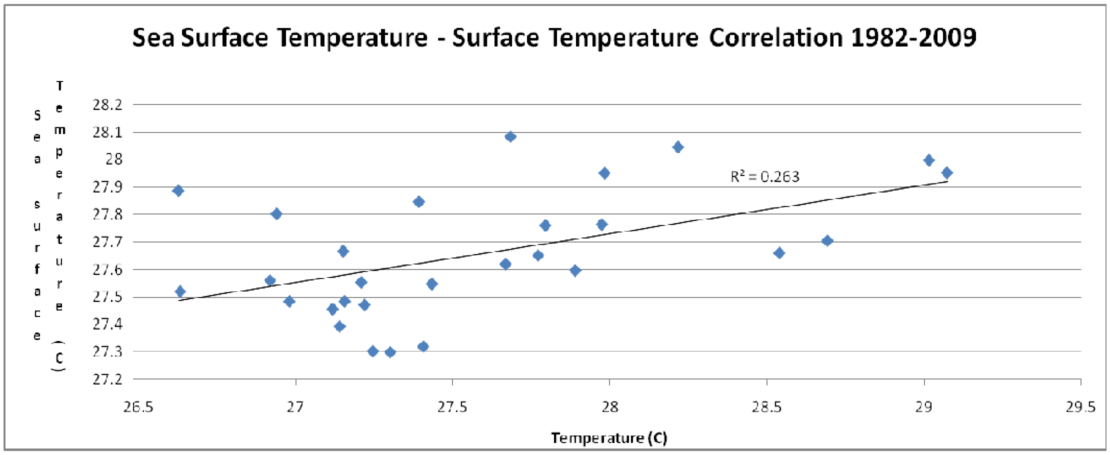


Figure 42 - Sea Surface Temperature – Surface Temperature Correlation 1982-2009

iii. Statistical Analysis: Sea Surface Temperature – Surface Temperature

A t-test was conducted in order to determine if the averages of the sea surface temperature and surface temperature are significantly different. The t-test shows that the averages of both factors correlate by ***56%***. The result of the test is shown below:

t= 0.594
Standard Deviation= 0.886
Degrees of Freedom = 54

The probability of this result, assuming the null hypothesis, is 0.56

SEA SURFACE TEMPERATURE:
Mean = 81.8
95% confidence interval for Mean: 81.44 thru 82.12
Standard Deviation = 0.408
Hi = 82.6 Low = 81.1
Median = 81.7
Average Absolute Deviation from Median = 0.333

SURFACE TEMPERATURE:
Mean = 81.6
95% confidence interval for Mean: 81.30 thru 81.98
Standard Deviation = 1.18
Hi = 84.3 Low = 79.9
Median = 81.3
Average Absolute Deviation from Median = 0.907

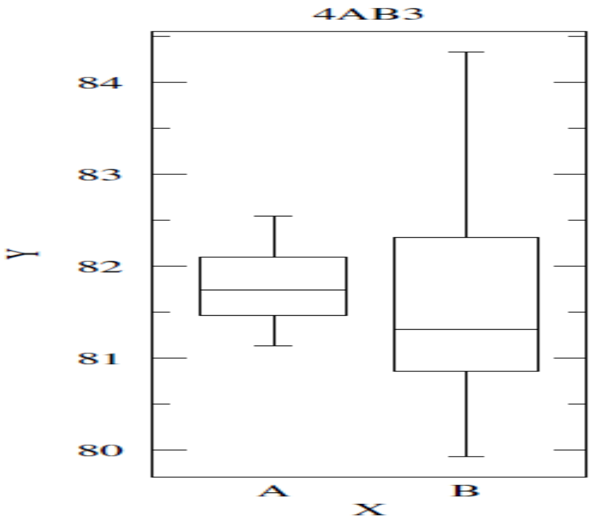


Figure 43: Box Plot Sea Surface Temperature (A) – Surface Temperature (B)

iv. Extreme Events

A study of extreme events associated with sea surface temperature in the Caribbean region was also conducted. Figure 44 shows that during the past 15 years there has been an increase in the number of tropical cyclones formed in the Caribbean. One of the reasons behind the increase in number of storms is warm water. High sea surface temperatures are the main energy source of these storms. The warmer the water, the stronger the storms become. There were 235 storms in the region over the last 15 years (1995-2009). Table 11 shows a distribution of the hurricanes, tropical storms, and tropical depression and their frequencies.

Table 11*:* Tropical Cyclones Distribution from 1995 to 2009

Cyclone	Total Storms	Average / Year	Percentage
Hurricane	110	7-8	47.41%
Tropical Storm	94	6-7	40.51%
Tropical Depression	28	2-3	12.07%

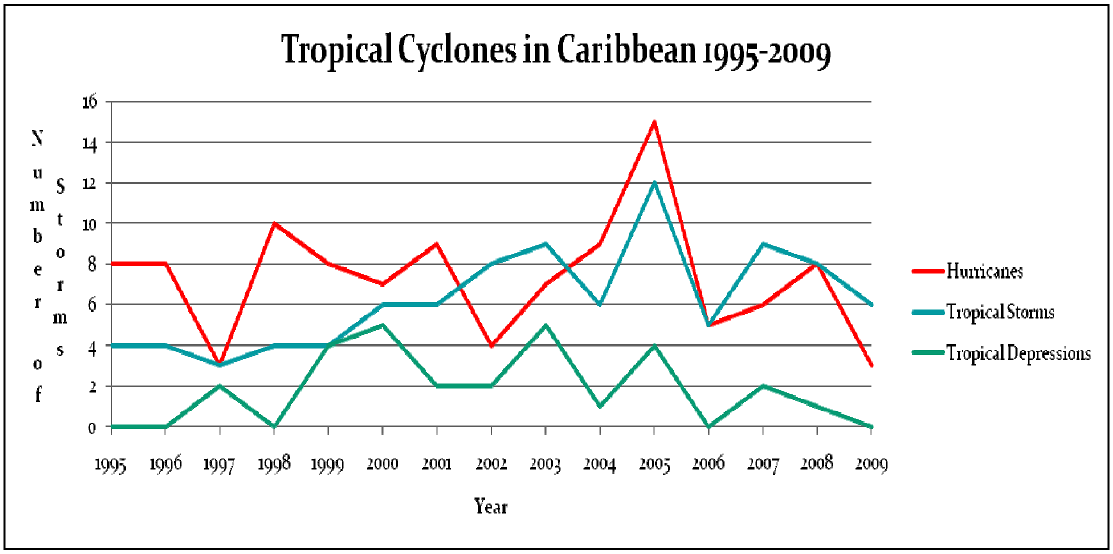


Figure 44 - Tropical Cyclones in the Caribbean Region 1995-2009

The formation of tropical cyclones in the Caribbean region is affected by the presence of El Niño and La Niña. The presence of El Niño in the region translates to a low number of tropical cyclones formed compared to La Niña, where the number of tropical cyclones is high. The years in which El Niño was present during the period 1995-2009 were 1997, 2002, 2006, and 2009. La Niña was present during the other years.

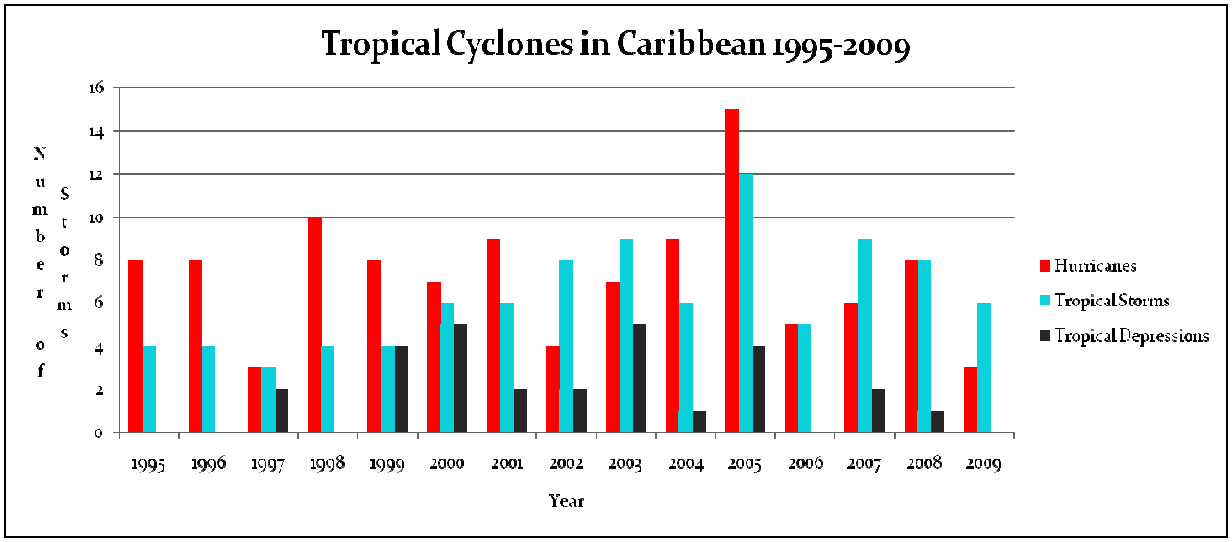


Figure 45 - Tropical Cyclones in the Caribbean Region 1995-2009

During the past 15 years, 20 tropical cyclones directly or indirectly affected Hispaniola Island. Four tropical cyclones affected the island during El Niño and 16 tropical cyclones affected the island during La Niña. The island has 80% probability of being affected directly or indirectly by a tropical cyclone during La Niña compared to a 20% probability during El Niño. Figure 46 shows the tracks of some cyclones over the island.

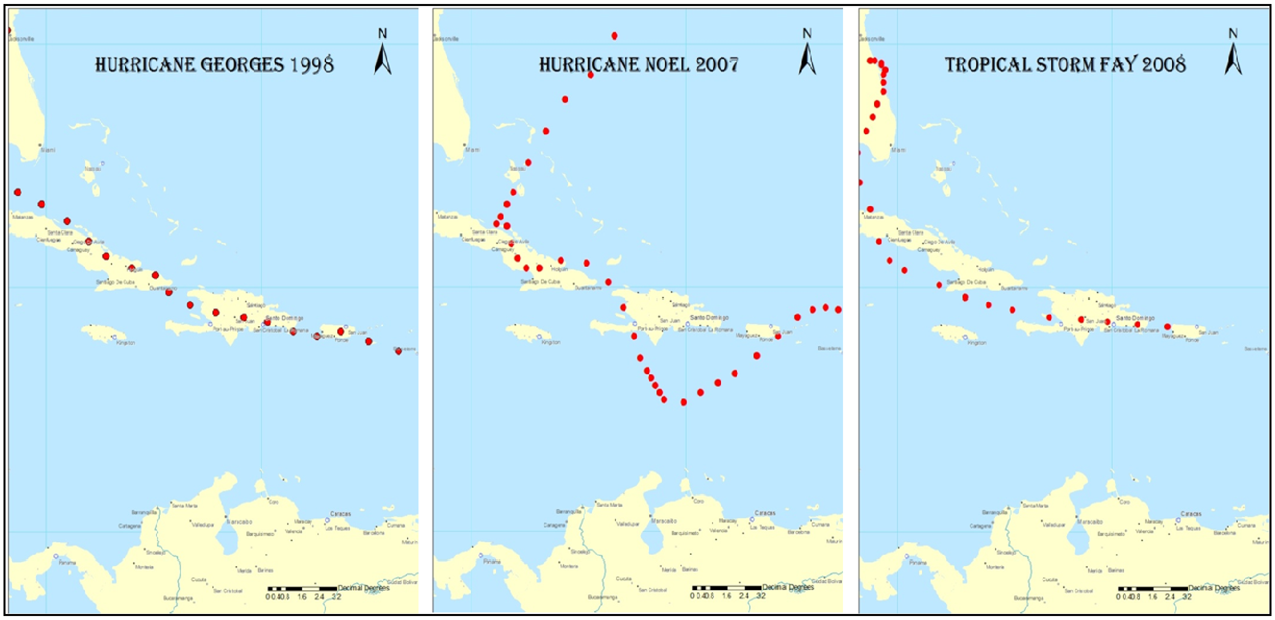


Figure 46: Tropical Cyclone Tracks over the Hispaniola Island

d) Karsha Walker

i. Dew Point Temperature Analysis

Dew points are indicates of the amount moisture in the air. The higher the dew points, the higher the moisture content of the air at a given temperature. Dew point temperature is the temperature to which the air would have to cool in order to reach saturation. When the air cools, moisture is removed by means of condensation and the result is the formation of small water droplets such as dew, fog or even precipitation. Therefore, as dew point temperature increase (more water content), evaporation decreases.

In conducting a 30-year dew point temperature analysis using data acquired fro the Barahona NCDC station; Figure 47 shows a gradual increase in dew point temperature. Since 1979 there has been approximately a 10% increase.

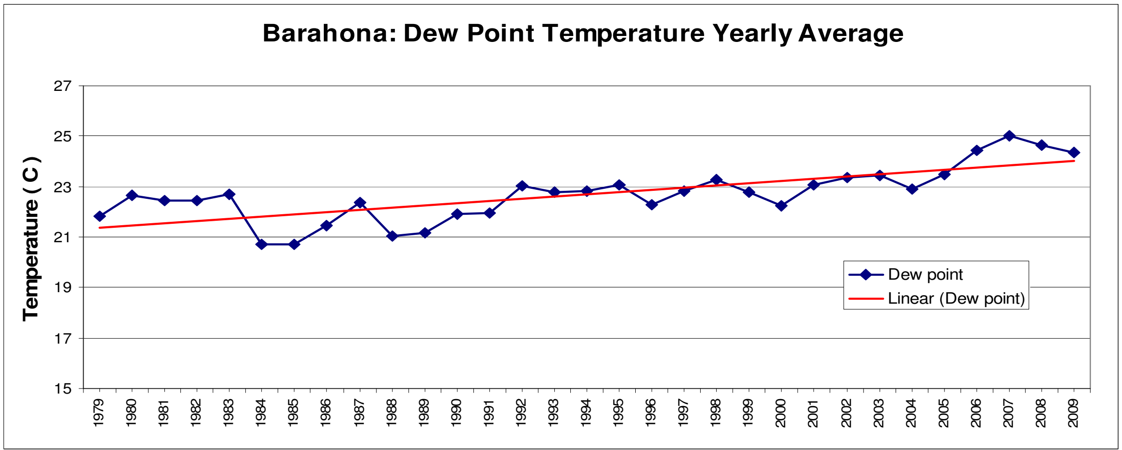


Figure 47: Barahona 30-year Dew Point Temperature, 1979-2009

Focusing on the overall climatology of the region, dew point temperature is approximately 15% higher during the rainfall season in September than in February which is the dry season.

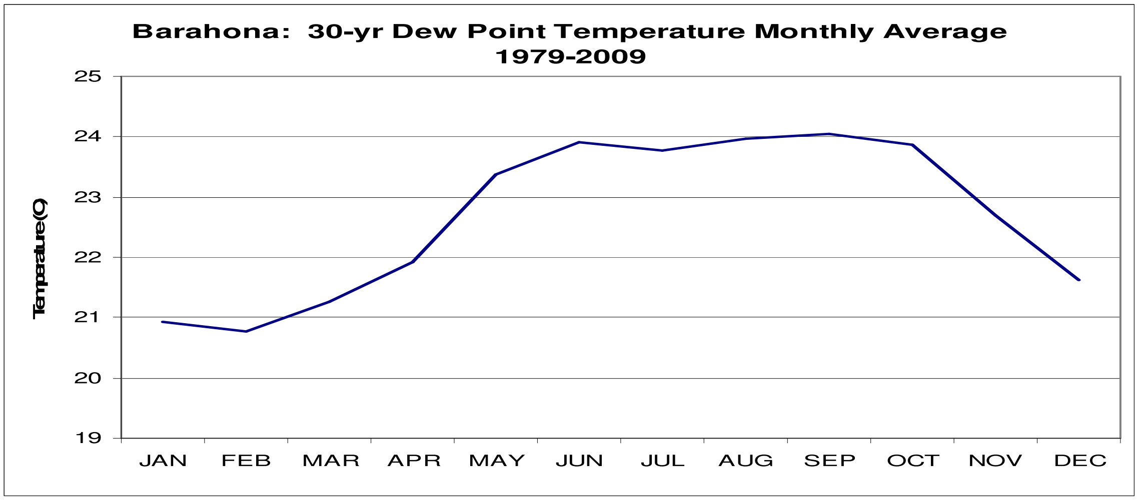


Figure 48: Climatology- Barahona Dew Point Temperature, 1990-2009

e) Summary Surface Area and Climotogical Findings

- Lago Enriquillo has grown 49% from its size at 2004 to 333 km^2 at the end of 2009.
- Lago Enriquillo is 17% larger than its size at 1984 of 276 km^2 at the end of 2009.
- Lago Enriquillo has grown about 10 meter on both east and west coasts.
- Lake Sumatre has grown 15.8% from its size of 115.96 km^2 at 1984 to 134.26 km^2 at May 2010.
- The expansion of Lago Enriquillo based on 2004 to 2009 analysis is 66% toward the east coast, 27% to the west coast, 9% to the north coast, and 13% to the south coast.
- Lake surface area is changed after hurricane or heavy storm events.
- At 2004, it was the common trough for lake surface area, precipitation, and SST, and after 2004 all three factors starts to increase together.
- Lago Enriquillo and Lake Sumatre revealed a similar growth trend from 1996 to 2009.
- The correlation between change of precipitation and lake surface area is 0.42 from 1984 to 2009, thus no clear indication of correlation
- Annual average precipitation has increased by 50% since 1979 to 2009 and since 1990-1999, there has been a 62% since 1980 to 2009
- Changes are more evident locally, near the region of interest, in the dry and late rainfall seasons.
- Not evidence of significant changes in extreme events
- Mean temperature seems to be increasing in the region of interest, reflected mostly in maximum temperatures.
- Possible causes:
    a) Global warming (see SSTs & next slide)
    b) Land use changes (see next analysis)

This may be associated to increases in regional precipitation.

- Maximum temperatures are expected increase evaporation rates from the Lake.
- Dew point temperature has increase by 10% since 1979, thus resulting in less evaporation.

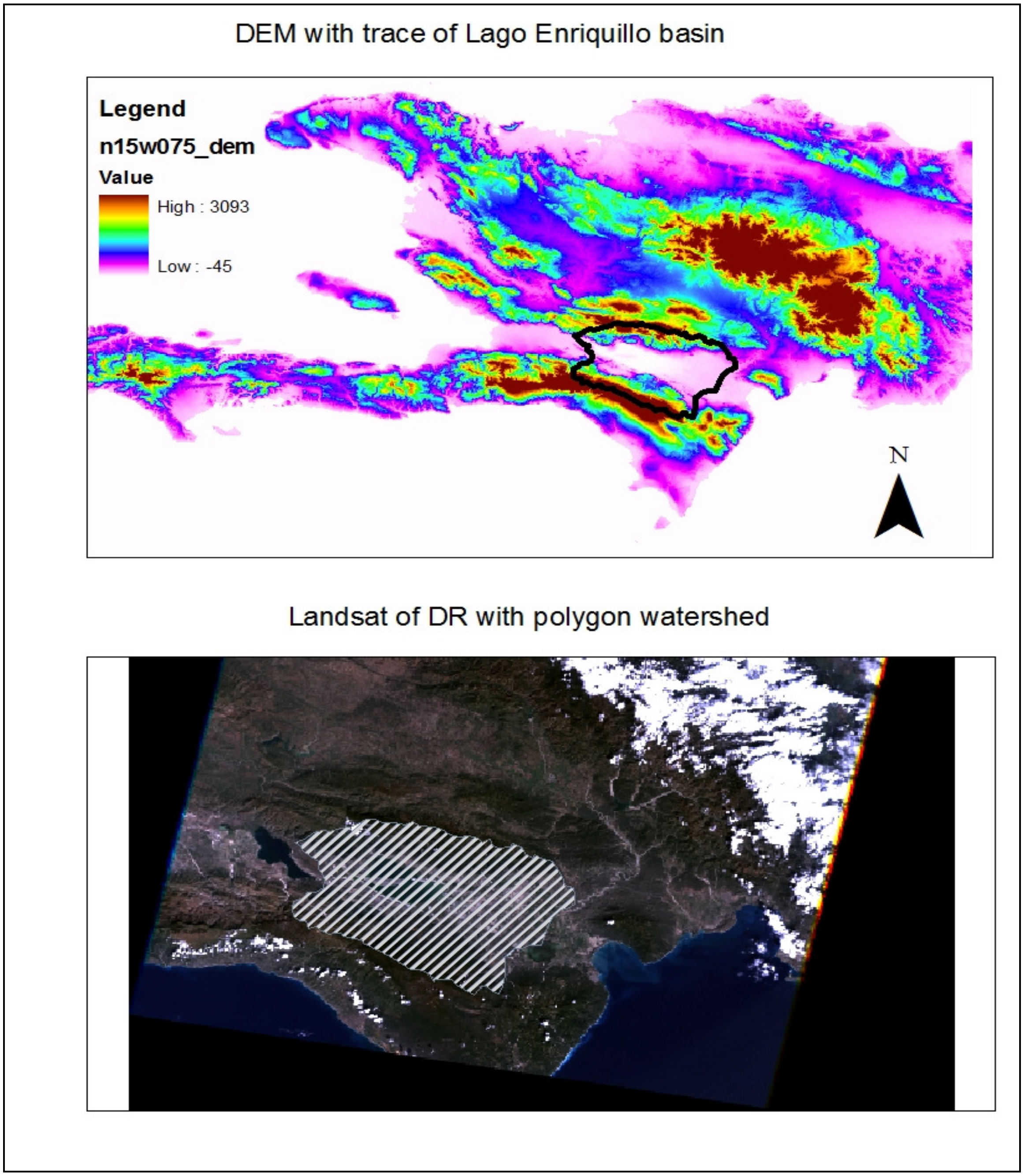
f) Gary Bouton

i. Land Use and Runoff Land Classification

To identify pixels in the Lago Enriquillo River Basin that contribute to runoff by land use changes I needed to use Landsat imagery because it had a high resolution of 30m. I also cut the images to just the watershed of the lake basin as pixels outside of this region do not contribute to the peak flow volume flux in lake levels. Using mapping tools I can visualize these changes through remote sensing techniques and then post process images to give a picture of the vegetation and land use that occurs in study years of 1984, 1998, 2010. Run off values can then be attributed to their land use classified coefficients and then measured and weighted to give a total contributing run off value for the Lago Enriquillo watershed. This can then be compared for the years chosen to try to ascertain what is happening to the land changes in correlation with flooding events or as we see in 1998 an evaporation issue.

The use of Landsat image database was chosen because of the historical images that we could draw comparisons against with some collected images for the Dominican Republic dating back to 1984. Landsat is a valuable to for historical marking because all images from the series use similar band make up which is good for measuring land use, vegetation indices, and even flooding because of its pretty high spatial resolution of 30 meters.

Once enough useful images are aquired; that is images devoid of a lot of cloud cover, look for a method of snipping these images to just the region of the lake watershed only. To do this I used HydroSHEDS Digital elevation model or DEM. The HydroSHEDS DEM is based on very high resolution spectral data that is used to delineate elevation from NASA's Shuttle Radar Topography Mission (SRTM). Using this SRTM data, HydroSHEDS is able to point out maximum elevation points along offering a suite of geo-referenced data sets (vector and raster) at various scales, including river networks, watershed boundaries, drainage directions, and flow accumulations. I used this data to acquire the watershed border of the Lago Enriquillo region and traced it and saved it as a polygon for use in cutting out the Landsat images using the clipping polygon function in ArcMap. In ArcMap‘s toolbox under Spatial Analyst tools you can find a function called Extraction which allows the user to input a raster file and to cut it by polygon, which is how I obtained my watershed only Landsat images as seen in Figure 48.



DEM with trace of Lago Enriquillo basin

Landsat of DR with polygon watershed

Figure 49 - *Figuring out Watershed*

Figure 49 shows the top image which is the HydroSHED data along with the DEM information in which the watershed of Lago Enriquillo is derived from, which I traced and created the polygon of the watershed which you see in the image below. This allowed me to cut all Landsat images to just the region I was interested in and only study those pixel changes.

After the images have been cut I created composite bands into which I could investigate the images for when I post processed them for Land Use Classification. I created (4, 5, 3 bands good for soil and vegetation measurements) composite and a (7, 4, 2 bands for “greenness”) composite to look at land type and vegetation brightness.

In post processing method of defining pixels in watershed by land use type functions for unsupervised classification under Multivariate functions for class clustering. This function allowed to user to input different raster files (bands) to create an image in which they could group pixels together based on their distance from each other and relation of “likeness”. I could choose how many different bins I wanted to create, “classes”, and how many iterations you wanted to loop the function for with a minimum threshold set for sorting unclassed pixels. Peaks are the class unique fingerprint so that similar peaked pixels are binned together. Dropped least significant clusters and reassign to most likely matched classes. Maximum Likelihood was used to make sure proper variance between class densities for chosen numbers of bins. Ground truthing was done with use of Google earth and Band combination (4,5,3) where classes were combined and defined based on visual observation.

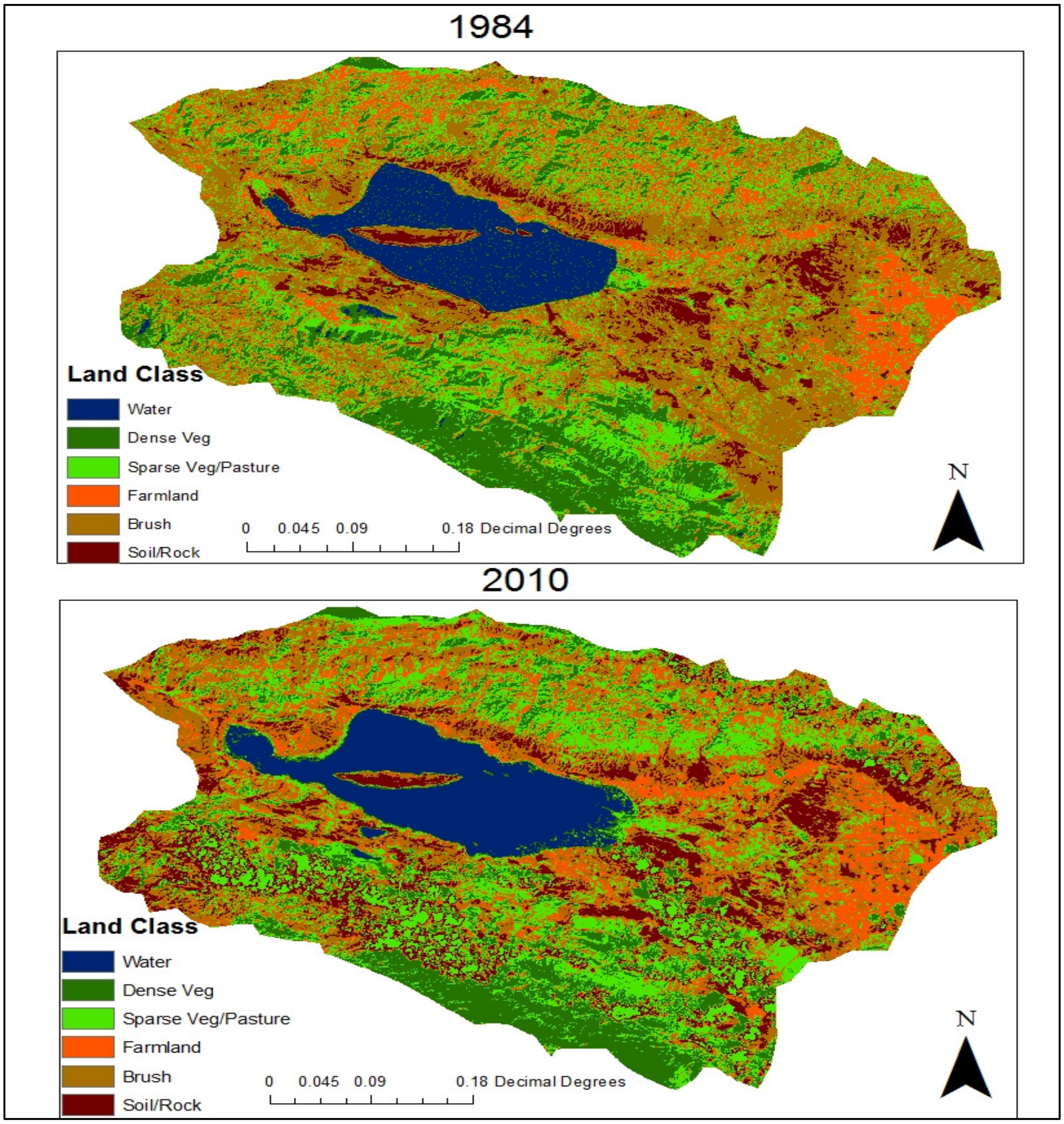


Figure 450 - *Land Classification of Land Usage 1984 and 2010 Non-drought Years*

In figure 50 I have paired two images of land classification from 1984 and 2010 because of their similar precipitation profiles and the similar size of Lago Enriquillo. I have stuck with 6 classes of land types; Water, Dense Vegetation, Sparse Vegetation, Farmland, Brush, and Soil/Rock. This was done so I could later weight all these land types by their Run off Coefficients based on their total land area in the watershed. We can see easily that soil/rock and brush make up areas of the basin more prone to erosion because of the larger slops of the north and southern borders of the lake. To the east of the lake is where the most density of farmland is found and you can see the increase from 1984 to 2010 in these images, more so along the edges of the lake itself. Just west of the major part of the farmland is mixed marsh and shrub growth that seems to be affected by rainy season erosion. Compared with 1998 it can be observed that more rain produces more patches of bare soil that might further effect continuing downpour in later months.

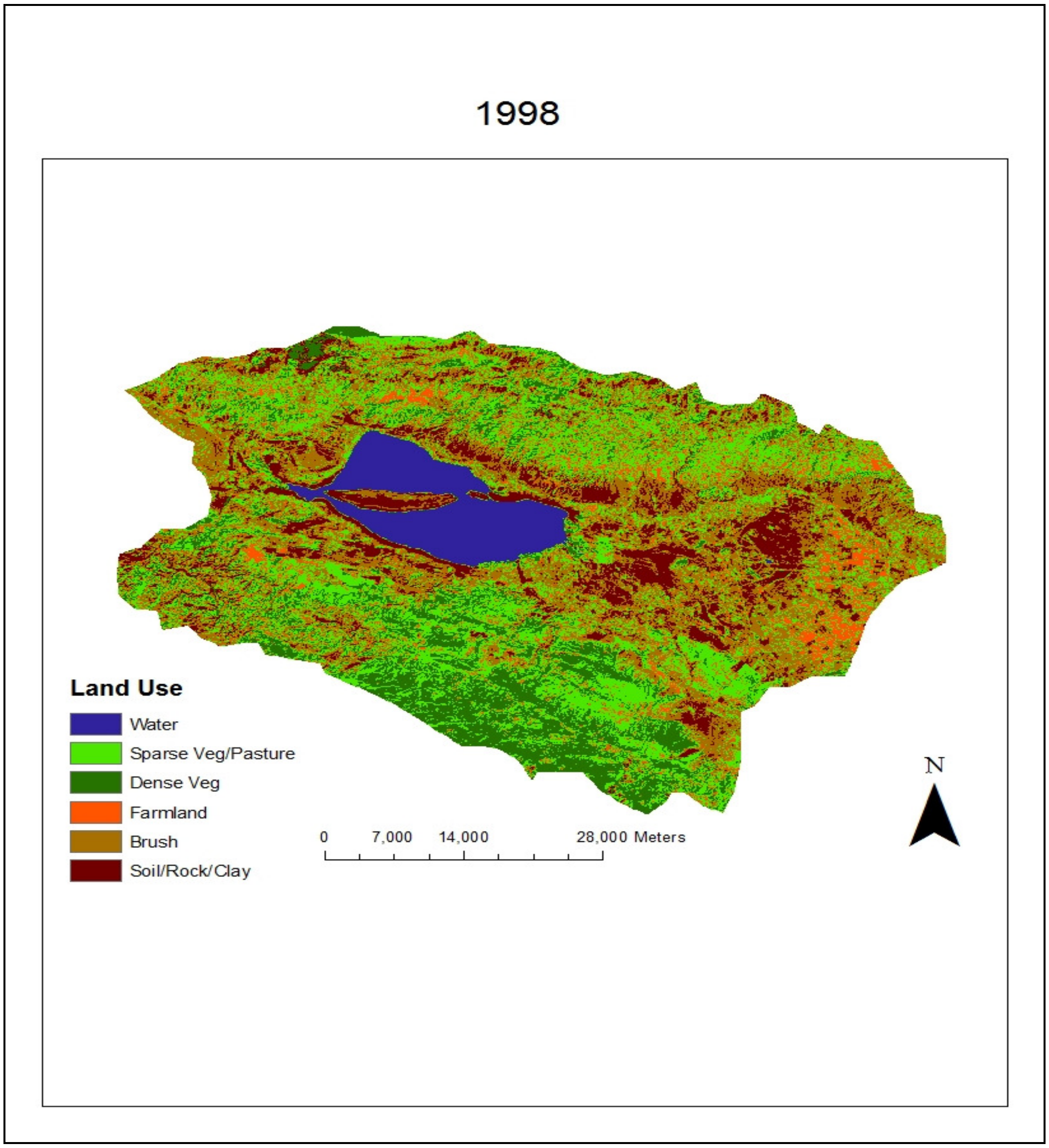


Figure 51 - *Land Classification of Land Usage 1998 Drought Year*

In figure 52 you can see that the density of farmland in the eastern part of the basin has lessened as you saw earlier in the paper this was a period of extreme drought to the region, as can be noted in comparison with 1984 and 2010 images that there is the missing of small water reservoirs just south of the lake.

Table 12 - *Weighted Run Off for observation years 1984, 1998, 2010*

1984					
Land Type	**Pixel Count**	**Area (m^2)**	**Land Use Area (%)**	**Runoff Values**	**Runoff/Area**
Water	286088	257479200	8.411450991	0	0
Dense Forest	641143	577028700	18.85064359	0.18	0.033931158
Sparse Forest	900485	810436500	26.47571882	0.25	0.066189297
Farmland	384100	345690000	11.29316268	0.42	0.047431283
Shrub	907126	816413400	26.67097498	0.31	0.082680022
Soil, Rock	282231	254007900	8.298048938	0.85	0.070533416
TOTAL	***3401173***	***3061055700***	***100***	***Weighted Runoff***	***0.300765177***
1998					
Land Type	**Pixel Count**	**Area (m^2)**	**Land Use Area (%)**	**Runoff Values**	**Runoff/Area**
Water	227232	204508800	6.680989176	0	0
Dense Forest	579861	521874900	17.04885344	0.18	0.030687936
Sparse Forest	977860	880074000	28.75066925	0.25	0.071876673
Farmland	338751	304875900	9.959828565	0.43	0.042827263
Shrub	794374	714936600	23.3558834	0.31	0.072403239
Soil, Rock	483095	434785500	14.20377617	0.85	0.120732097
TOTAL	***3401173***	***3061055700***	***100***	***Weighted Runoff***	***0.338527208***
2010					
Land Type	**Pixel Count**	**Area (m^2)**	**Land Use Area (%)**	**Runoff Values**	**Runoff/Area**
Water	328863	295976700	9.669105335	0	0
Dense Forest	589582	530623800	17.3346666	0.18	0.0312024
Sparse Forest	888359	799523100	26.11919476	0.25	0.065297987
Farmland	425695	383125500	12.51612311	0.43	0.053819329
Shurb	602385	542146500	17.71109555	0.31	0.054904396
Soil, Rock	566289	509660100	16.64981464	0.85	0.141523424
TOTAL	***3401173***	***3061055700***	***100***	***Weighted Runoff***	***0.346747537***

Table 12 shows the result of counting each class's pixels and then calculating their area and then weighting their run off values based on their percentage coverage in Lago

Enriquillo Lake Basin. We can see through the yearly progression of land use that the weighted runoff value has risen which would conclude that with the same amount of rainfall more precipitation would flow into the lake via run off. Runoff Values were taken from the USGS website and they are waited on the slope of counters of the Lake Watershed per the run off coefficient table and the land type that occupies that slope region.

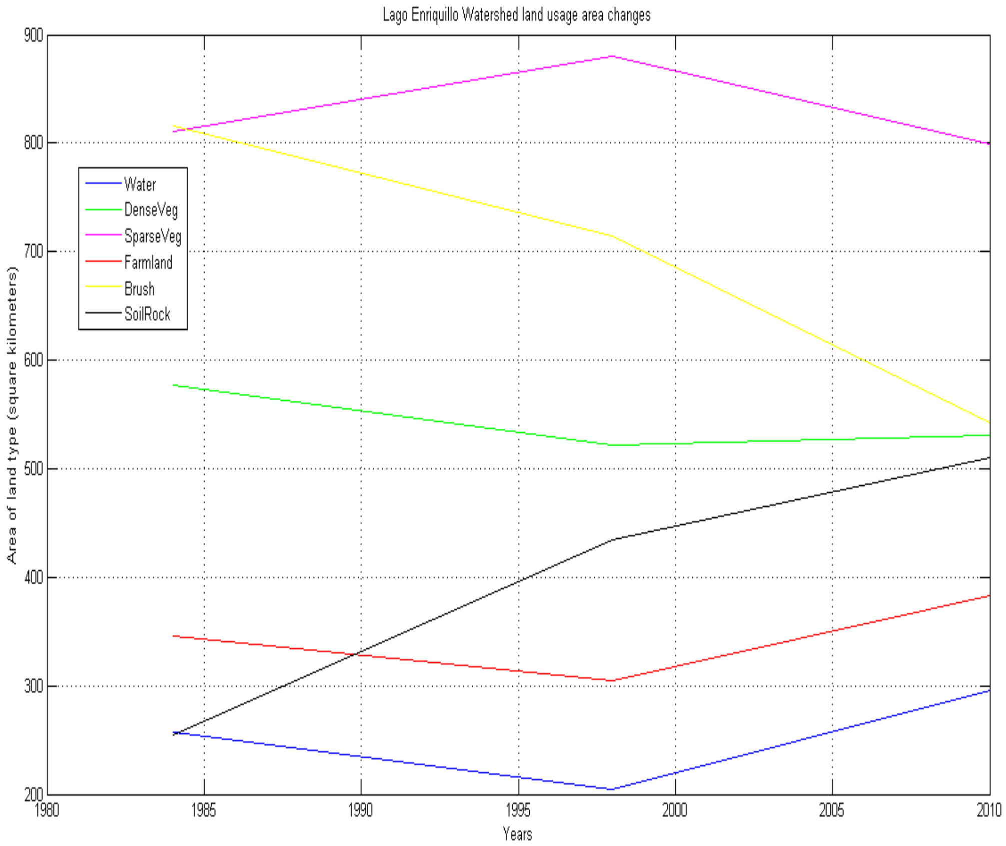


Figure 52 - *Land Changes by Area (km^2) 1984, 1998, and 2010*

The prior tables land area was then put into graph form where changes could be seen on graphical basis. Noting that 1998 is a drought year you can see the decline of the area of water matches that of farmland and dense vegetation. Moving into 2010 in which we are seeing higher than average precipitation we see again a rise in water area and also a similar trend in farmland. It is interesting to note is the decline of brush and the rise of soil and rock which could mean that increased run off has produced severe erosion and changed the landscape of the Lago Enriquillo region which would also account for the rising total runoff numbers.

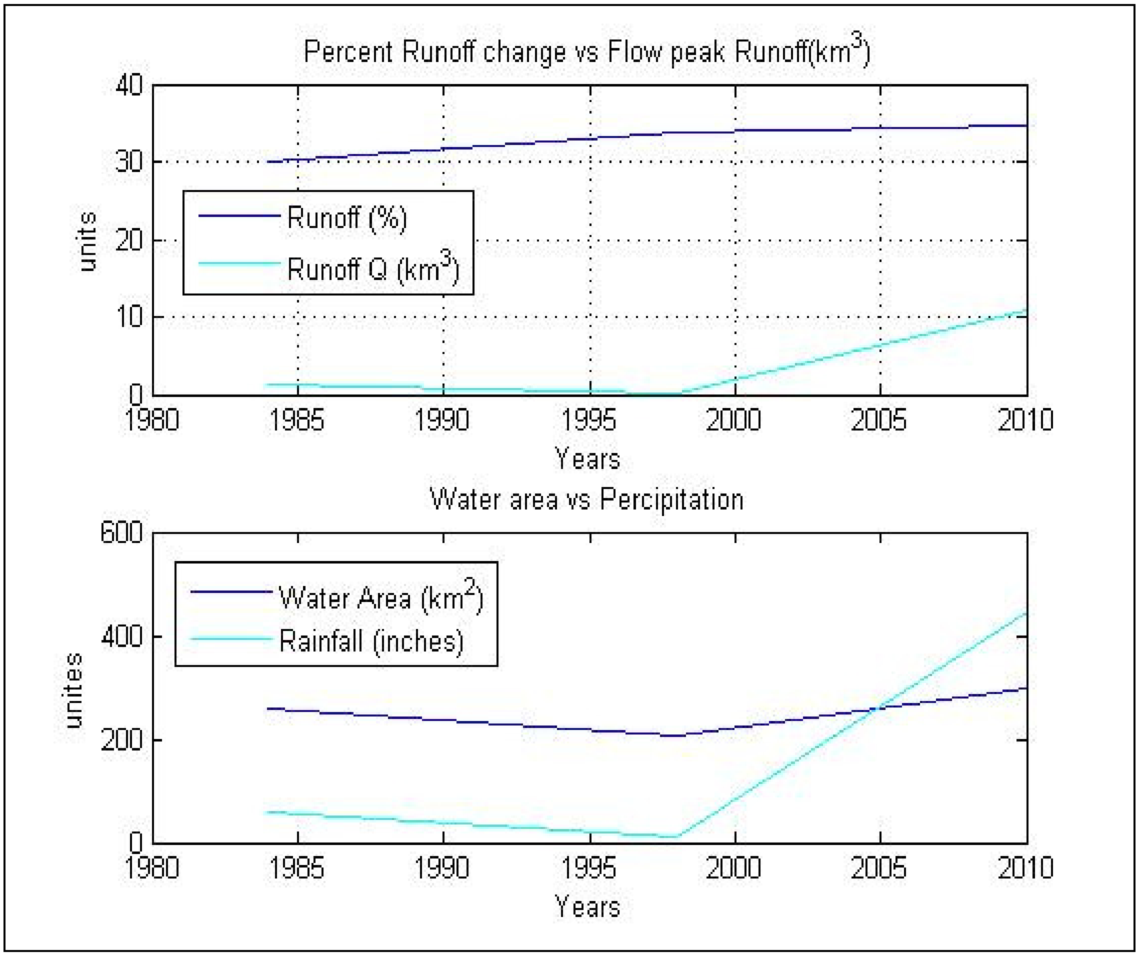


Figure 53 - *Runoff and Rainfall 1984, 1998, and 2010*

Figure 53 highlights the correlations of high rainfall with high runoff with a rising weighted basin runoff factor to the land. This also has a linear relationship with the water area found in the watershed. If rainfall was constant peak runoff (Q) would only then be affected by differences in the type.

ii. Hydrological Model Analysis and application

A simple Hydrological model of the lake's behavior was created to try and understand the mechanics of its growth and to try to estimate the contribution from any runoff from nearby river systems that during extreme events my over run their natural course and flood into temporary rivers which empty into the lake.

In thinking of variables that attribute to a Lake's growth we looked at a program called HY-SIM which models the behavior of watersheds. Breaking down the program we found many of the needed input variables were missing so a simpler version was made that simulates the same characteristics of HY-SIM without the known contributing flow rates of nearby rivers.

Run off values were taken from the land usage classification study for the years 1984, 1998, and 2010 and were progressed and trended linearly to find values for other nearby years when looking at lake changes over time. Since we could visually measure the lakes changes area from year to year all we had to do was to multiply by an average change in lake level to get a volume time scale which we could use to produce the missing variable of stream runoff flux during extreme events.

Hydrologic Lago Enriquillo Equation

$$\frac{D}{dt}(Lake\ area) = RF + RO + Qfl - Eva$$

- Where Lake change;
- D/dt(Lake Area) = can be turned easily to volume changed over time based on height observations matched to known contour levels
- RF = Direct rainfall
- RO = run off from runoff calculated per contributing pixel
- Eva = Evaporation by using Penman method combined with historical data
- Qfl = will be the flood potential of nearby rivers rates into Lago Enriquillo during flood event, needs to be determined
- This is based on prior assumption that there is no natural inflow/outflow of lake.

Evaporation determination

To model evaporation we used Penman equation which we modified.

$$\lambda\ ET_0 = \frac{\Delta}{\Delta + \gamma}(Ka) +$$

$$\frac{\gamma}{\Delta + \gamma} f(v)(e_s - e_d)$$

1. Lambda = latent heat of vaporization
2. Delta = slope of vapor-temp curve
3. Gamma = psychrometric constant at T & P
4. Ka = Constant Flux difference between Solar and Soil
5. V= wind speed m/s
6. es = saturation vapor pressure @ T
7. ed = actual vapor pressure @ T and RH

Input variables were supplied by the database from Barahona which was accessed through the National Climate Database Center. They were then simulated over years for confidence testing to see if evaporation returns fell within known evaporation limits being 2.2 meters a year and a low of 1.2 meters a year on high and low average respectively.

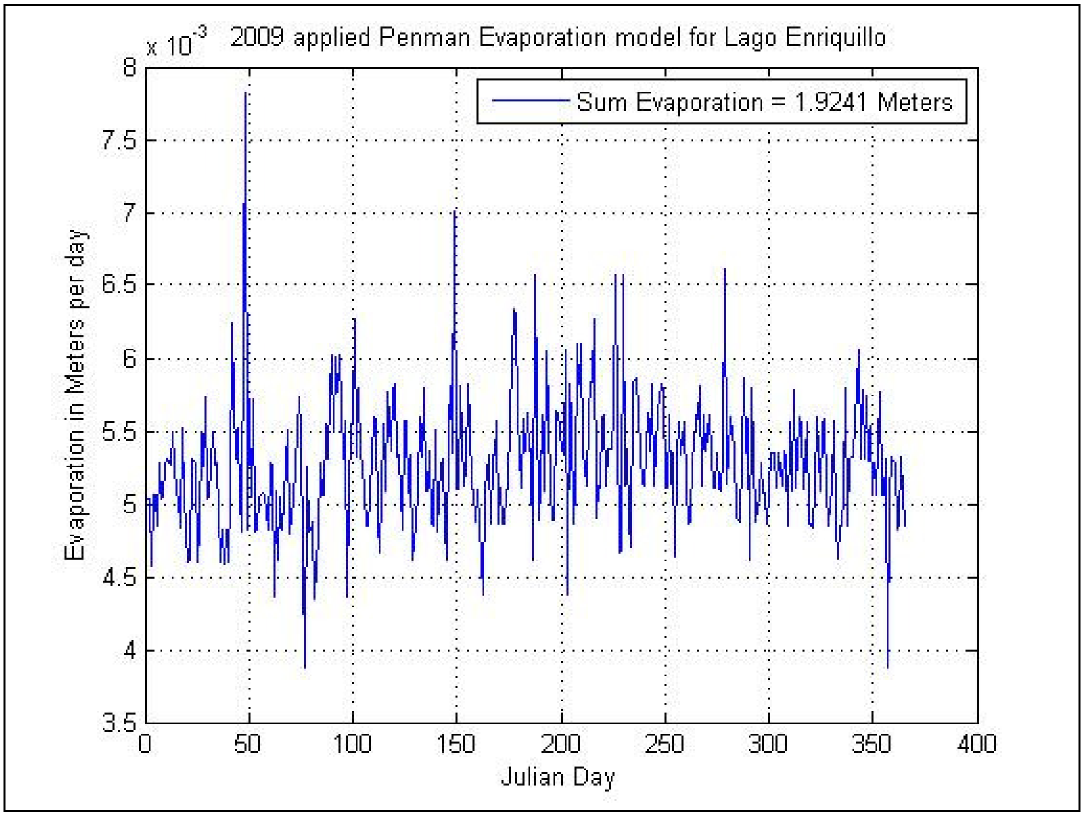


Figure 54 - *Evaporation model of Lago Enriquillo for 2009*

Runoff and Capture

By determining weighted runoff for years 1984 , 1998 we can use these constants to see if model works for predicting in year 1985 and 1999 to see if use of rational method is correct and evaporation model is well correlated in predicting successfully change in the Lake.

Where;

1. Runoff is Qp = C*I*A

   Qp = peak flow rate of volume

   C = weighted yearly runoff coefficient

   I = Intensity of rainfall

   A= Area of watershed

2. Capture is RF= LA*I

   LA = Lake area at time year

   I = Intensity of rainfall

Model can be assumed to be correct when there is no extreme rainfall event that causes unknown variable of extra flood from other local stream flow that model does not account for. Model is run for years in which extreme event rainfall is absent.

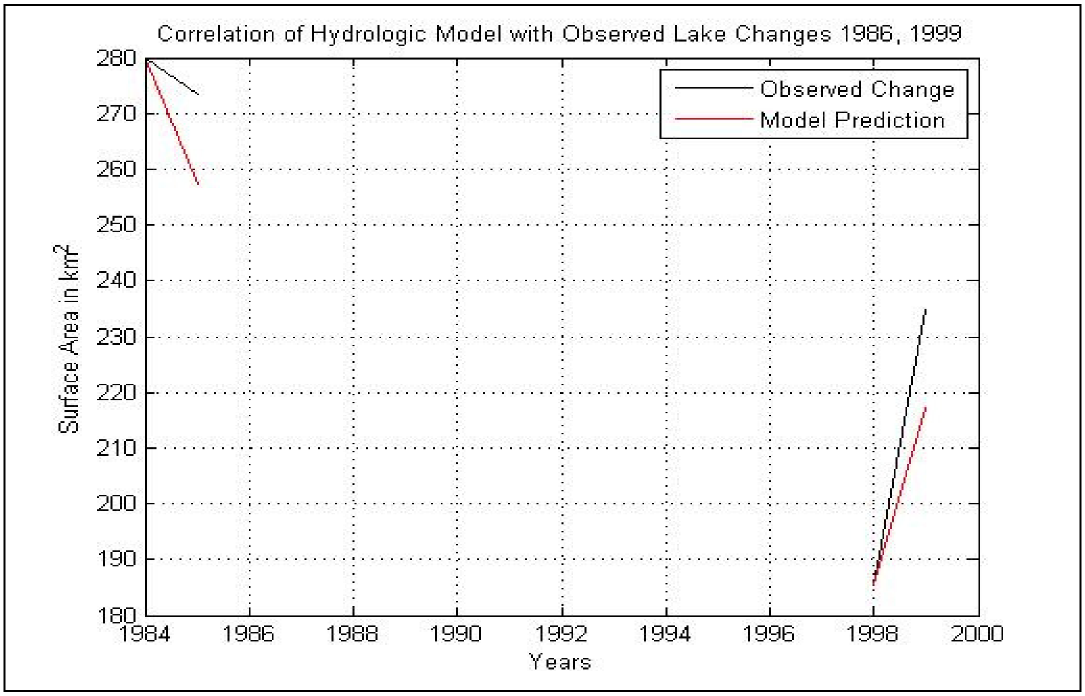


Figure 55- *Hydrological Model Yearly Change, Observed vs. Prediction*

The model produced these results

1985 Observed = 273.50 km^2

1985 Predicted = 257.21 km^2

Off 6%

1999 Observed = 234.86 km^2

1999 Predicted = 217.32 km^2

Off 8%

It can be concluded with some confidence that on a yearly change the model has good prediction ranges for years without extreme events.

Running Model for Full Year with multiple observation days in year

Table 13: Displays the Observation points in year for late 1985 to late 1986 in which model was run against to simulate if it could give a comparable realistic output as one we had measured from LANDSAT imagery

Year	Month	Day	Observation
1985	12	19	1
1986	1	20	2
1986	2	5	3
1986	2	21	4
1986	3	9	5
1986	4	10	6
1986	4	26	7
1986	7	15	8

Year	Month	Day	Observation
1986	7	31	9
1986	9	1	10
1986	9	17	11
1986	10	3	12
1986	10	19	13
1986	11	4	14
1986	12	22	15

.

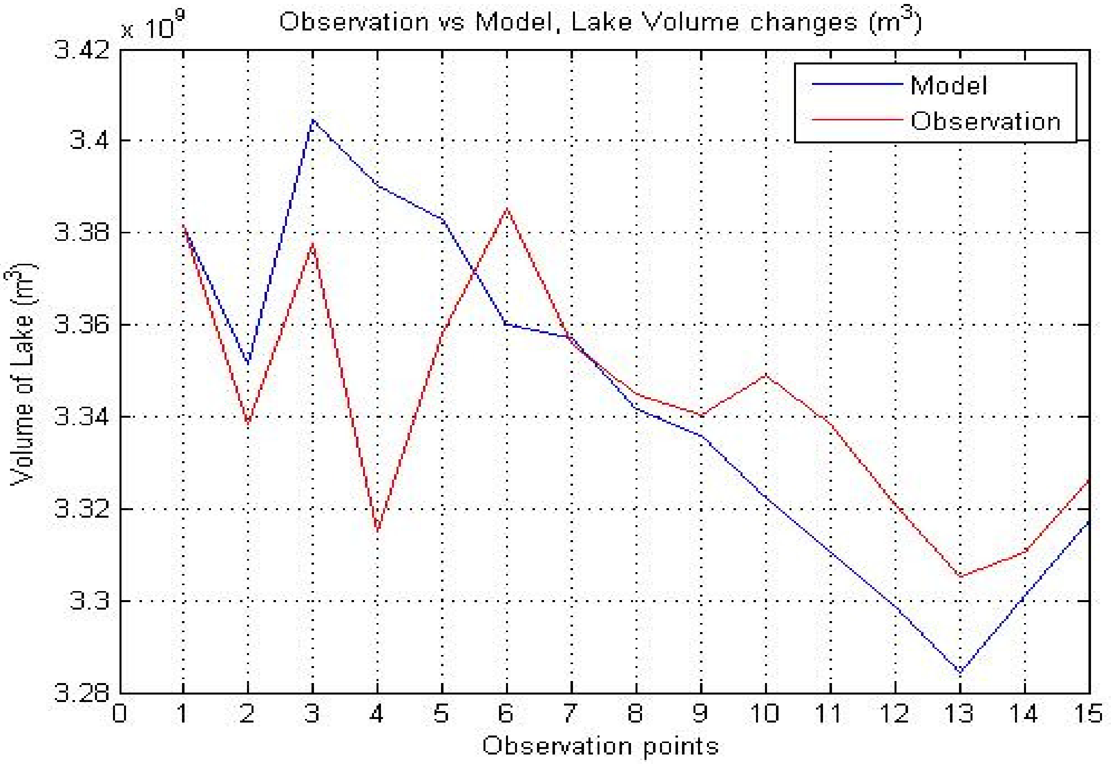


Figure 56: Displayed Data of observed lake volume versus model prediction based on weather data from Barahona station

Model has good correlation with observed Lago Enriquillo lake volumes and even displays same spiking and descending behaviors as even the lake experienced showing properly the mechanics of the dry season vs the wet season and coming to a similar final outcome on lake size in the end. Only anomaly is between observations 4, 5 and 6 in which short duration heavy precipitation shows the limitations of the model because there is no account being calculated of flooding into water basin from sources outside such as rivers.

Model run for stable and isolated drying phase of Lake 2001

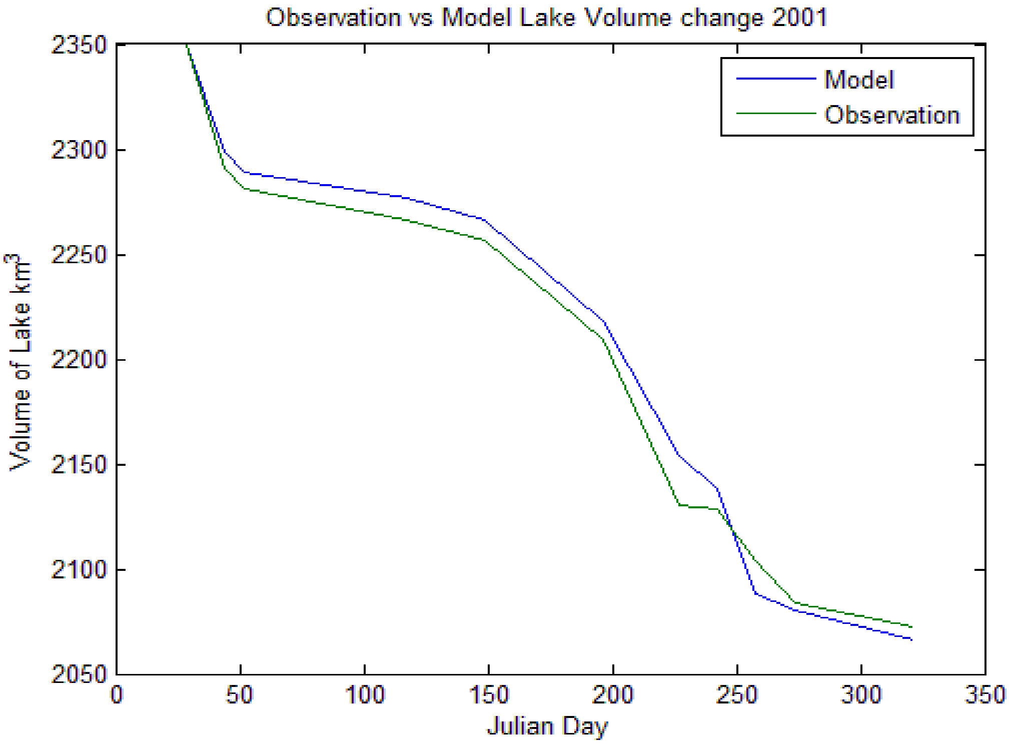


Figure 57: Model run in 2001 in a drying period versus observations

For model runs for stable drying periods in which instances of short terms flash flood rains do not enter into the model there is even better mechanical behavior or model with that of the observational volumes changes seen in the lake. The model is highly reliant on accurate weather data which can be read into Penman Evaporation Algorithm which the model heavily relies upon to simulate the drying in the lake regions. When accurate data is not able to found, some creativity must be considered in deriving things such as dew point and humidity from other known variables or even substituting other weather station data in to fill the holes in.

Runoff from streams

- Issues are found in model when Extreme Events (Precipitation Intensities that exceed the capacities of local river systems nearby) which create another source of volume added to the Lake

- Since it is not recorded about the Qp capacity of nearby rivers (ie Yaque del Sur), the model cannot take into account any extra perceptive inventory

- Qfl can be estimated by finding excess flow by rearranging simple Hydrology equation to Qfl = Lake Volume Change - Runoff – Lake Capture +Evaporation

- Example below is for Tropical Storm Fay event on Aug 17-18 2008

Table 14 - *Weighted Run Off for observation years 1984, 1998, and 2010*

Lake Volume change (m^3)	550909600
Runoff Area (m^2)	2761055700
Rainfall Total (m)	0.354076
Q=CIA (m^3)	338988560.7
Days to Image	17
Evaporation	0.0896156
Evaporation (from lake)	26884684.93
Lake Capture (m^3)	106222800
Volume (RF + RO -Eva)	418326675.7
Overrun (m^3)	132582924.3

What is illustrated in table 6 above is that Overrun can be calculated from the model by solving for the unknown variable in the original equation of missing flux from outside sources, which are not direct surface runoff or captured rain water. We can then use the same model to estimate the contributing volume added by local rivers and streams from flooding from their watershed into the Lago Enriquillo watershed. In the case of Tropical Storm Fay we see that 132,582,924.3 cubic meters of water was unaccounted in the model and missing in the direct observed change in the lake volume as seen in before and after satellite images of the region.

iii. Recommendation and Forecasting

If in future that Lago Enriquillo happens to recede past current levels it is suggested that the current water line be used as a designated buffer in which the red regions is considered a high risk flood plain and is off limits to agriculture, business, and improvements to save monetary, and physical losses unless improvements to capture of runoff from nearby streams is improved.

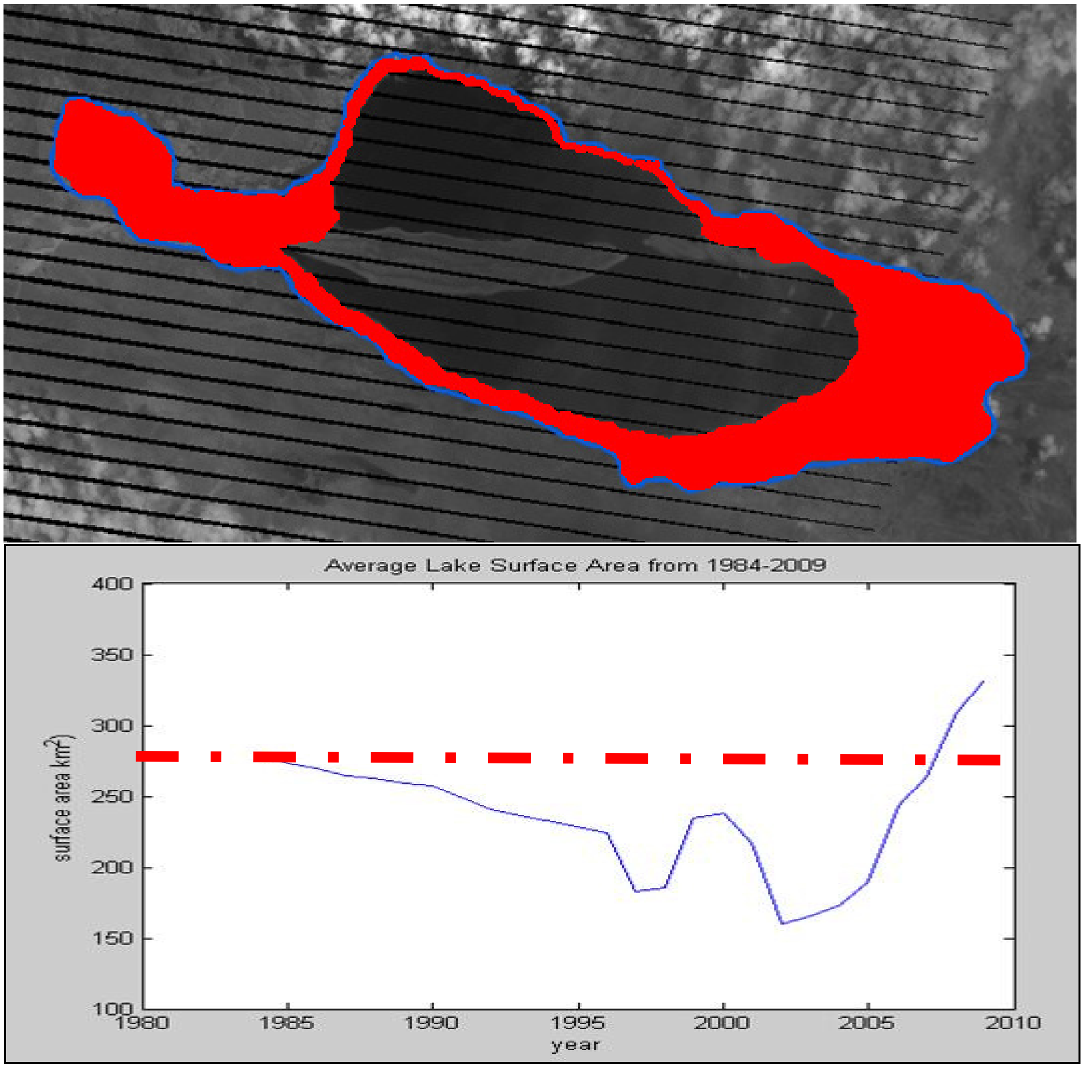


Figure 58 - *Placement of Flood Plain, or restricted access to improvement zone*

In figure 58 we have designated a red flood plain zone based on the reoccurrence of the lakes behavior to have a historical water line that is consistent with its modern placement today. Not allowing improvements to be made in the red region would save the country money in terms of rebuilding, relocating families that would eventually need assistance if they chose to move within the red delineated region of the lake watershed.

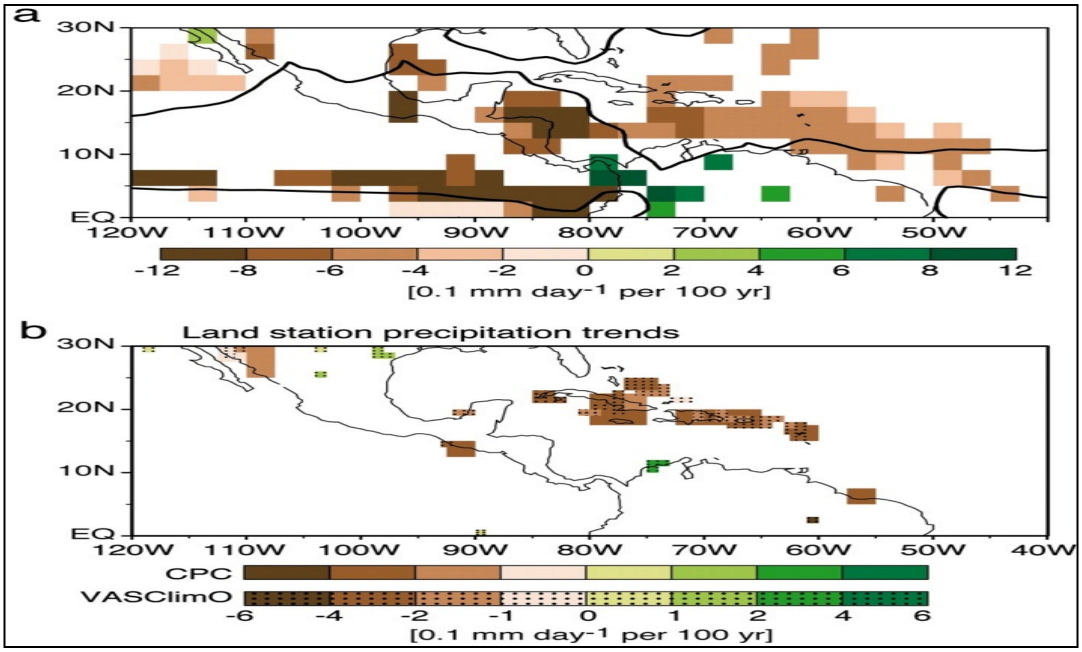


Figure 59 - *Precipitation trend from observed estimates for JJA. (a) Climate Prediction Center Merged Analysis of Precipitation satellite-only product for 1979–2003. The 4 mm day−1 contour from the climatological average over this period is shown in black for reference. (b) Gridded station data (partial land and island coverage only) from two data sets: Climate Prediction Center (34) (CPC; 2.5° resolution, 1950–2002) and Variability Analyses of Surface Climate Observations (33) (VASClimO; overlaid at 1° resolution, 1951–2000). Shading indicates regions exceeding the 95% significance level by the Spearman-rho rank-based test. Note that the color bar in a is at double the interval of that in b [Neelin]*

In using our hydrological model for forecasting a conservative estimate of the lakes surface area for a 25 year outlook we used the climate predictions modelled by JD Neelin, et al. Their expected number values tested with confidence were pumped into our model and we considered the weighting of precipitation trends in regards to expected hurricane events as sea surface temperature rise, but instead took the side of caution and wanted to test if our model could give a conservative picture of a future of Lago Enriquillo.

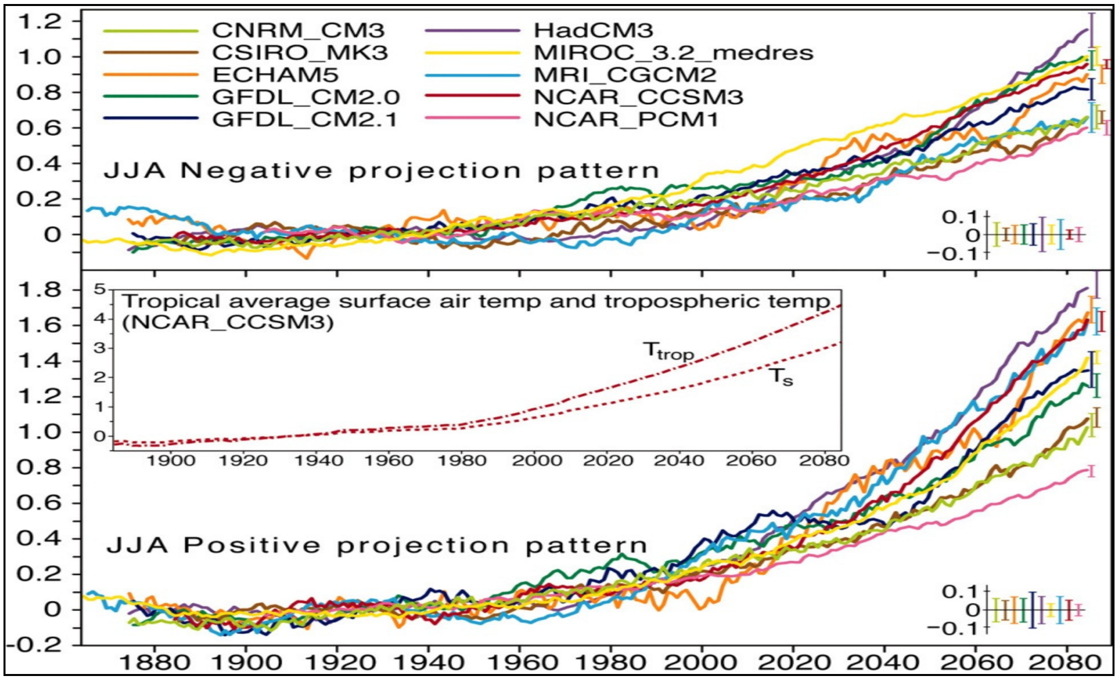


Figure 60 - *Temperature trend from observed estimates Neelin J D et al. PNAS. Amplitude of dry and wet precipitation changes (30-year running mean, relative to 1901–1960) for JJA from 10 ocean–atmosphere climate models for the Special Report on Emissions Scenarios A2 global [Neelin]*

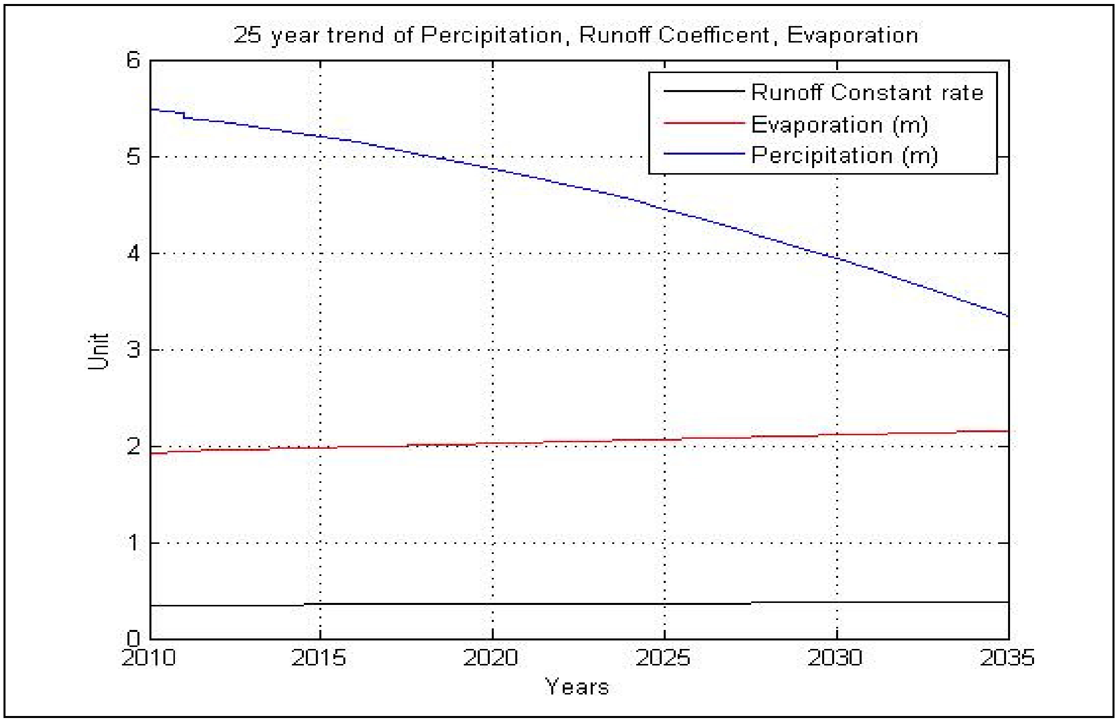


Figure 61 - *25 year Trend from Model of Evaporation, Precipitation, and Runoff Constant*

Figure 61 highlights the modeled changes in expected temperature rises effecting evaporation rates, our linear estimated runoff weighted factors based on land usage change rates and a downtrend in expected Caribbean rain outputs. Pumping these values into our hydrological model showed that at the end of a future 25 year cycle at a conservative estimate we see a net increase of 35 square kilometers of Lago Enriquillo's waterline according to surface area estimates.

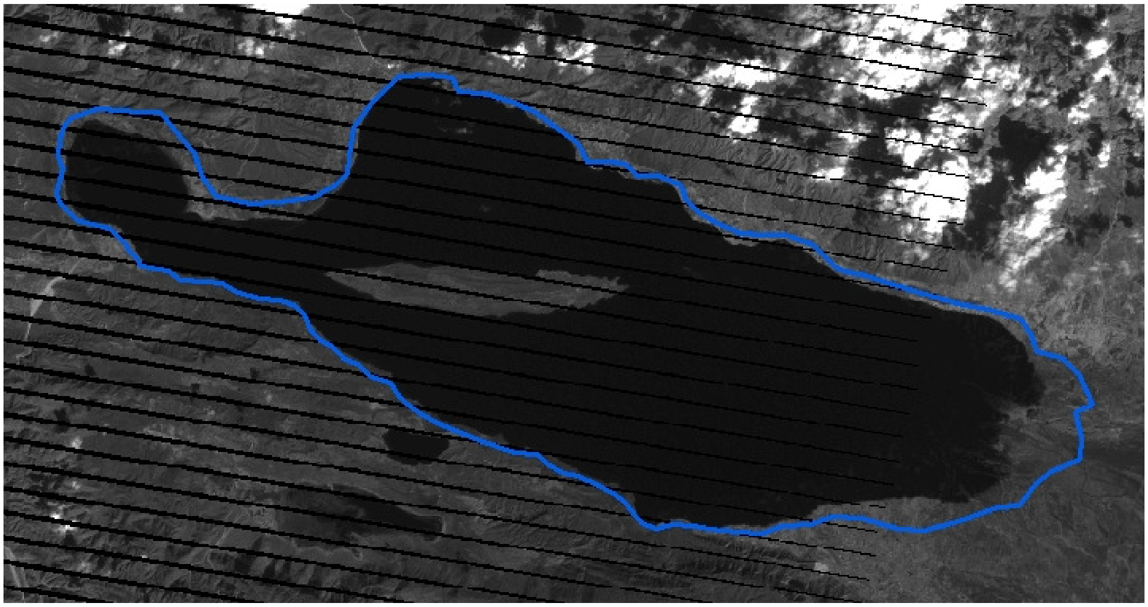


Figure 62 - *25 year trend from model with Visible Estimate*

Figure 62 shows a Landsat image of the current condition of the lake and the blue border shows the expected shape and size in a 25 year forecast according to the rates of change the lake increases in cardinal directions based on year by year observations.

g) References

1. Lugo, A. (2000). Effects and Outcomes of Caribbean Hurricanes in Climate Change Scenarios. International Institute of Tropical Forestry, Puerto Rico, USA. Received November 21, 1999; accepted April 7, 2000.
2. Buck, D., Brenner, M., et el. (2005). Physical and chemical properties of hypersaline Lago Enriquillo, Dominican Republic. Verh. Internat. Verein. Limnol. 29 0000–0000 Stuttgart, January 2005.
3. International Fund for Agricultural Development (IFAD). (1998). The Dominican Republic for the Southwestern Small Farmers Project – Phase 2. Executive Board - Sixty-Fifth Session. Rome, 2-3 December 1998.
4. Medrano, P. (2009). Assistance to Victims of Lake Enriquillo Flooding. DOMINICAN REPUBLIC 10846.0, 21 May 2009.
5. "Enriquillo Lake's rise swallows crops, crocs pose threat." *Dominican Today*. Economy - 25 February 2009.
6. Hernández, J. ROA PROJECT, ROLE OF AGRICULTURE IN DEVELOPING COUNTRIES, DOMINICAN REPUBLIC CASE STUDY. JULY 30, 2003.
7. "Torrential Rains and Flooding in the Dominican Republic and Haiti." The Pan American Health Organization - Promoting Health in the Americas. October 21, 2005.
8. Dominican Republic - Environmental Priorities and Strategic Options Country Environmental Analysis
9. MacCraken, M. (2006). Global Climate Change and the Dominican Republic. Climate Institute, Washington DC. Jume 3, 2006. http://www.climate.org/topics/climate-change/climate-change-dominican-republic.html
10. http://www.rimd.org/advf/documentos/4b63411256f9b.pdf
11. Al-Khaier, F. (2003). Soil Salinity Detection using Remote Sensing. International Institute for Geo-Information Science and Earth Observation).
12. Comarazamy, Daniel E. and González, Jorge E. On the Validation of the Simulation of Early Season Precipitation in the Island of Puerto Rico Using a Mesoscale Atmospheric Model. University of Puerto Rico, Mayagüez, PR and Santa Clara University, Santa Clara, CA